INVESTIGATING WATER-LAND-ECOSYSTEMS NEXUS FOR WATERSHED INTEGRATED MANAGEMENT

Dissertation

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*) Either the German or the Italian form of the title may be used.

Passavamo sulla terra leggeri come acqua, come acqua che scorre, salta, giù dalla conca piena della fonte, scivola e serpeggia fra muschi e felci, fino alle radici delle sughere e dei mandorli o scende scivolando sulle pietre, per i monti e i colli fino al piano, dai torrenti al fiume, a farsi lenta verso le paludi e il mare, chiamata in vapore dal sole a diventare nube dominata dai venti e pioggia benedetta. A parte la follia di ucciderci l'un l'altro per motivi irrilevanti, eravamo felici.

Sergio Atzeni, Passavamo sulla terra leggeri

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Finally, I want to thank Giovanna: I feel very lucky to be by your side.

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List of Abbreviations and Symbols

BBS	Bangladesh Bureau of Statistics
CAP	Common Agricultural Policy
CRED	Centre for Research on the Epidemiology of Disasters
CTA	Consumption To Availability
DEM	Digital Elevation Model
DPSIR	Driver, Pressure, State, Impact, Response
EF	Environmental Flow
ES	Ecosystem Services
ESF	Ecosystem Function
ESP	Potential Ecosystem Services
FAO	Food and Agriculture Organization
FBS	Food Balance Sheet
GDP	Gross Domestic Product
GIS	Geographic information system
HER	Human Energy Requirements
HRU	Hydrological Reference Unit
ICWE	International Conference on Water and the Environment
IPCC	Intergovernmental Panel for Climate Change
ISO	International Standard Organization
IWRM	Integrated Water Resources Management
LCA	Life Cycle Assessment
LU	Land Use
Lup	Land use update
MEA	Millennium Ecosystem Assessment
MODIS	Moderate Resolution Imaging Spectroradiometer
RBA	River Basin Authority
SRTM	Shuttle Radar Topography Mission
SUPARCO	Pakistan Space and Upper Atmosphere Research Commission
SWAT	Soil Water Assessment Tool
UNCED	United Nations Conference on Environment and Development

USLE	Universal Soil Loss Equation
WES	Water Ecosystem Services
WF	Water Footprint
WFA	Water Footprint Assessment
WFD	Water Framework Directive
WSF	Water Scarcity Footprint
WSI	Water Stress Index
WTA	Withdrawal To Availability

γ	psychometric constant (kPa/°C)
Δ	slope of the vapour pressure curve (kPa/°C)
Appl	quantity of applied substance
c_max	maximum acceptable concentration
c_nat	natural concentration
C_F	coarse fragment factor
C_{USLE}	cover and management factor
CWR_{green}	crop water requirement
CWU	crop water use
E_a	amount of actual evapotranspiration (mm)
e_a	actual vapour pressure (kPa)
e_s	saturation vapour pressure (kPa)
ET_0	potential evapotranspiration (mm/day)
ET_c	actual evapotranspiration (mm/day)
G	soil heat flux (MJ/m^2/day)
K_c	crop type coefficient
K_{USLE}	soil erodibility factor
LS_{USLE}	topographic factor
NSE	Nash Sutcliffe efficiency
PBIAS	Percent Bias Statistics
P_{eff}	effective rainfall

P_{USLE}	support practice factor
Q_{gw}	amount of return flow (mm)
Q_{surf}	amount of surface runoff (mm)
R^2	coefficient of determination the
R_{day}	amount of precipitation (mm)
R_n	net radiation at the crop surface ($MJ/m^2/day$)
RSR	Root mean square error and the standard deviation of measured data ratio
SW_o	initial soil water content (mm)
SW_t	soil water content (mm)
t	time (days)
T	temperature (°C)
U_2	wind speed at a height of 2 meters (m/s)
W_{seep}	amount of water entering the vadose zone from the soil profile (mm)
α	runoff factor

Introduction

Motivation and overall objectives

At the beginning of the third millennium, human actions let the control variables of several planetary boundaries leave the safe operating space (Steffen et al., 2015). A radical change in the human development paradigm is needed to cope with multiple environmental crises, understand their interrelationships and promote a fair coupling between human and nature. In this direction, the concept of nexus focuses on integrated analysis and management of different components of ecosystems such as water, land or energy (SEI, 2011). A deep understanding of the nexus is needed to provide the scientifically sound framework required to meet increasing multiple demands at the global scale (Rampa & Van Wyk, 2014), combining environmental protection and safety of society development (Bazilian et al., 2011).

Society strongly relies on the stability of ecosystems that can assure the provision of natural resources and ecosystem services, i.e. the benefits provided by nature for human well-being. This highlights the necessity of developing methodologies and tools to manage coupled human-nature systems without compromising ecosystems.

Water plays a key “nexus role” within the ecosystems, because it underpins a large set of benefits for humans such as food or energy production. While freshwater shortages have already begun to constrain socioeconomic development in some regions, many other regions have enough water availability, but they suffer of governance incapacity to tackle global changes (Mekonnen and Hoekstra, 2016). Among other global trends, population growth and the related increase in demand for agricultural production put further pressures on water resources. With biomass increasingly becoming a central resource for energy and food security in a, so-called, green economy, water acts as a fundamental state variable and at the same time a control variable of change (SEI, 2011). By 2030, under an average economic growth scenario and if no efficiency gains are assumed, global water requirements would grow from 4,500 billion m^3 today to 6,900 billion m^3, i.e. 40% above current accessible, reliable supply (WRG, 2009). This global figure is the aggregation of a very large number of local deficits, some of which show an even worse situation: one-third of the population, concentrated in developing countries, will live in basins where this deficit is larger than 50% (Addams et al., 2009). In addition, the share of the population facing water risks is projected to expand greatly due to climate change (IPCC, 2014). Extreme events, such as droughts and floods are already causing major water crises within the global systems, jeopardizing food security and influencing the energy sector. This suggests the necessity of analyzing the relationships and feedbacks among sectors in order to promote a more resilient and fair coupling of environment and society (Hussey & Pittock, 2012). Therefore, watershed management should reflect the multiple scales and dimensions of water-related issues, supporting strategies that combine the analysis of hydrological, energy-related and agricultural variables together with economic and social aspects, moving beyond a single sector optimization approach and looking at the various form of nexus among them.

As a first step, the following overall objectives are identified:

1. Examine existing water management frameworks and investigate their potential for adaptation and integration to deal with the nexus issues.
2. Develop operative analysis techniques by integrating approaches from different disciplines.
3. Apply the developed techniques to real case studies dealing with the various levels of complexity and different scales of analysis that characterize the nexus.

According to these objective, the following overall research questions are identified:

1. How can water management benefit from the **nexus concept**?
2. Which are the **scales of analysis**? How they are connected?
3. How can the nexus concept be translated into an **operative framework** of analysis for water management?

Based on the state of the art, in the paragraph 1.6 I identified the key points of my research and the methodologies to be used. Then, I elaborate three different case studies to deal with various nexus roles of water in watersheds. Specific research questions are identified for each case study representing a peculiar aspect of the nexus approach in water management. Similar to stereoscopy, where the combination of multiple points of view reveals an additional dimension that would not be otherwise visible, the thesis develops a holistic approach, where the integration of the different perspectives adopted allows getting useful insights into the overall behavior of the watershed analyzed.

Thesis structure

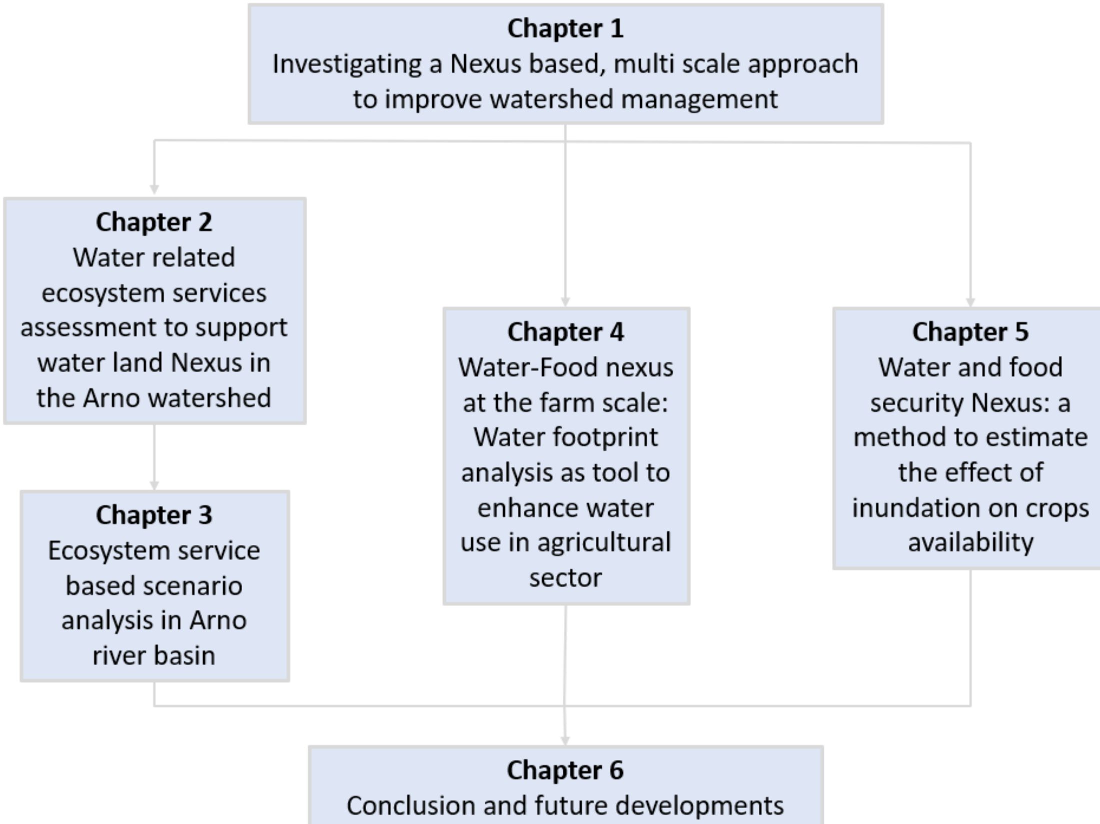

Fig.1 Outline of the thesis

The thesis is organized in six chapters assembled as depicted in Fig .1. The first chapter frames the thesis within the state of the art regarding water management and the nexus approach. Starting with the definition of the idea of nexus, it is then explored how this concept can be linked to water management. Existing approaches, coming from different disciplines (e.g. ecosociohydrology, ecosystem services theory) are introduced as the basic blocks to link the nexus concept and water management. The state of the art represents the foundation of the entire thesis, identifying the need for specific innovative developments that are dealt with in the following chapters.

Chapter 2 contains the first case study dealing with the assessment of water-related ecosystem services assessment to support the water land nexus in the Arno watershed. At catchment scale, I propose a methodology for evaluating water-related ecosystem services (ES), integrating ecohydrological evaluation with ES theory to support the water-land-ecosystem nexus in the Arno river basin.

Chapter 3 is based on the findings of the second chapter and develops an ecosystem service-based scenario analysis for assessing the effects of future developments in the Arno watershed.

In the fourth chapter I analyze the water-food nexus on the smaller farm scale, taking advantage of water footprint analysis as a tool for improving watershed management, enhancing the knowledge of human impacts on water resources, and for overcoming the lack of data regarding water use in agriculture.

The fifth chapter deals with the relationships between extreme flood event and food production. In this chapter, the water-food nexus is approached developing a method for estimating the effect of inundation on crop availability and showing the implications for watershed management.

The final chapter is dedicated to analyzing the implications of the thesis' findings and discussing their potential advancements.

1

State of the Art: exploring water-land-ecosystems nexus to improve watershed integrated management

1.1. Structure

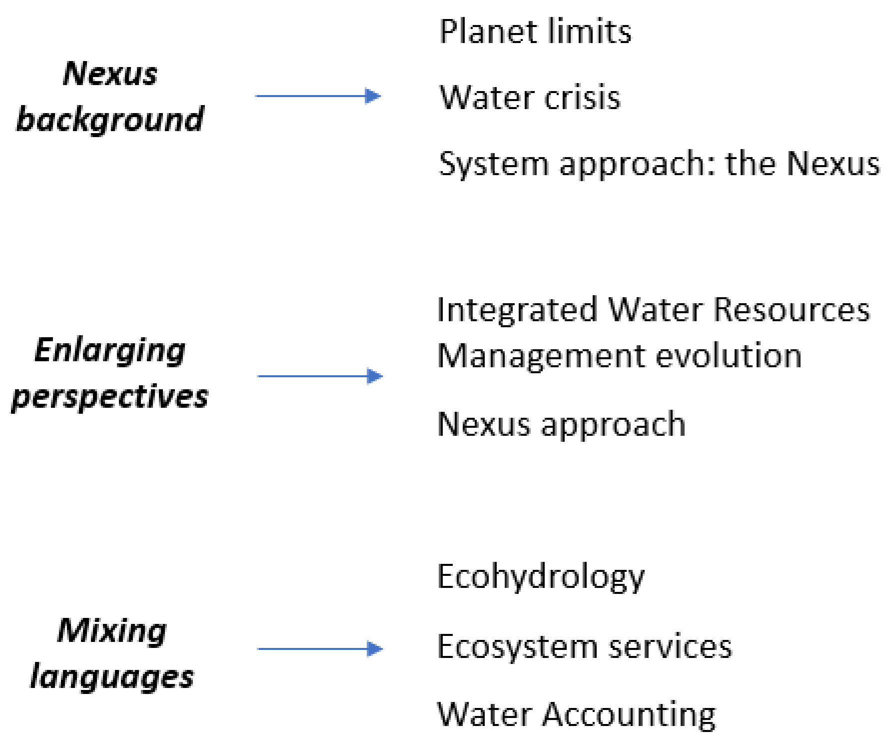

Fig. 1.0 Graphical abstract explaining the three main themes that constitute the state of the art review and the main concepts explored to identify the "building blocks" of the thesis

1.2. Nexus background

A new geological era, the so-called Antrophocene (Rockström et al., 2014), seems to be developing, and humans are the main drivers of this global evolution. However, it is not a new form of Humanism, but the awareness that technological evolution has led man to deal with the limitations of nature (Galimberti, 2002).

Using a doughnut, the economist Kate Raworth recently summarized the boundaries that define the human safe operating space (Raworth, 2015). This effective scheme (Fig. 1.1) represents the two limits within which natural resources management is bounded: (i) a lower boundary representing minimum level of resources needed to maintain human wellbeing, and (ii) an upper boundary representing the limits of our planet, i.e. its capacity of recovery, as defined by Rockström et al. (2009).

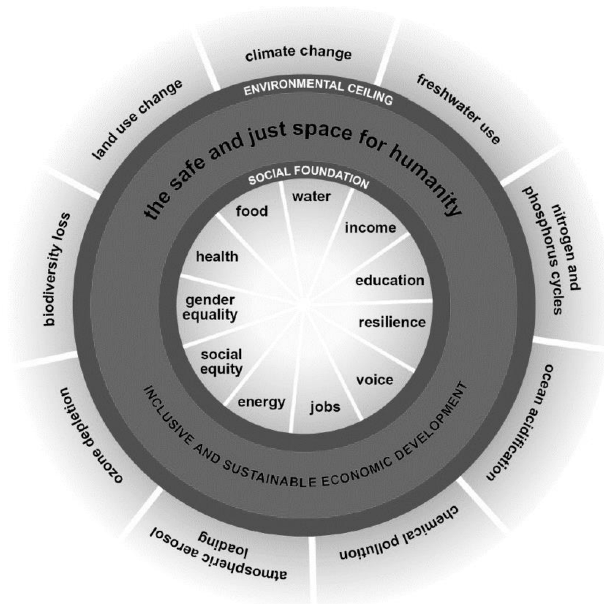

Fig. 1.1 Planet double boundaries (Raworth, 2015) The lower boundary represents the different human rights that should be assured to maintain human wellbeing while the upper boundary represents the limits of our planet, as classified by Rockström et al. (2009). All the different components of the inner and outer circle are interdependent, meaning that an overall view is needed to maintain humanity in its safe space.

Water represents an important part of the doughnut, playing a key role in the ecosystems, often being one of the main limiting factors of the social foundation of sustainability (Mekonnen and Hoekstra, 2016, Bazilian et al., 2011).

The World Economic Forum has ranked water as top three long-term risk in the last three years and showed how water is connected to the world's most severe problems (World Economic Forum, 2017, cf. Fig. 1.2). In particular it is possible to identify three main classes of water risk: two are related to the quantity of water available in a landscape (e.g. drought and flood), the third is related to the quality (e.g. pollution). Drought and flood represent extreme situations that can lead to the crisis of a water system and, as a consequence, of the water-related sectors (e.g. food security that can be damaged by water scarcity or inundations). Pollution can cause water system crises reducing the possibility of accessing the resources even in scenarios not characterized by water scarcity in quantitative terms.

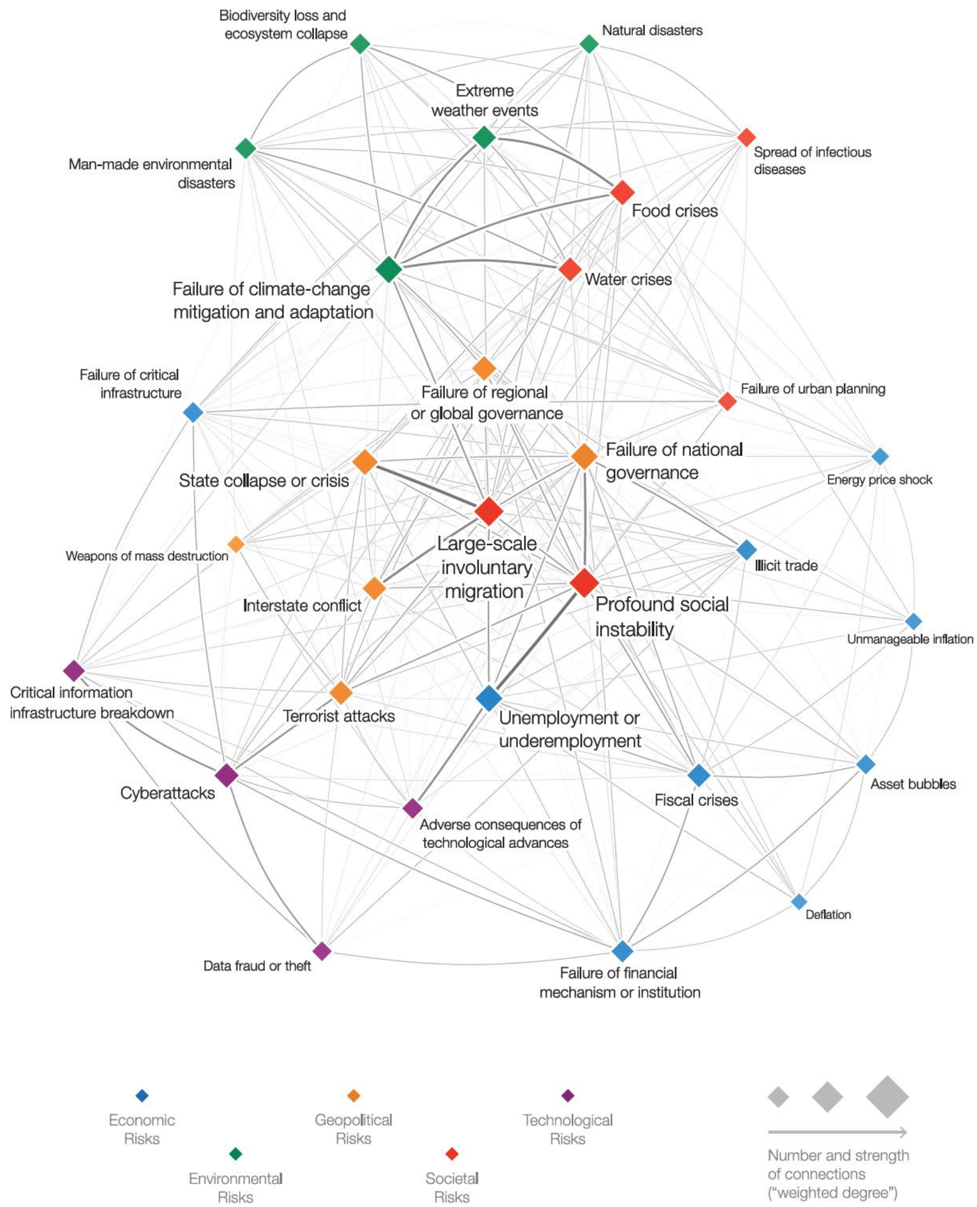

Fig. 1.2 Map of interconnections of risks (World Economic Forum, 2017). Water is represented as a societal risk (marked as red) that is connected with geopolitical and environmental risk (marked as green). Environmental change (such as extreme events) claim the necessity of management adaptation. A failure in adaptation causes an asymmetric coupling between the ecosystem and humans, exposing the latter to high water risk scenarios and connected food crises (size of markers represents connectivity of each risk and the weight of lines represents the intensity of the connections).

It is evident that water represents a "connection factor" linking many global issues. Therefore, water management should necessarily focus on this complex nexus of connections, dealing with the multiple risks associated with water resources.

1.3. Towards a systems approach: the nexus

As already underlined, water-related issues can be interpreted from many perspectives. As an isolated element, water is usually interpreted as a resource that needs to be divided and allocated, trying to reduce the risks associated to its variability. At the same time, if we look at water in relation with the surrounding landscape, water assumes other values, being a part of a larger web of connections, i.e. the ecosystems.

The two perspectives summarized above simplify a dichotomy that, at least for western philosophy history, dates to the Ancient Greek world, when the basis of the contrast among scientific reductionism and a holistic approach were posed (Bateson, 1979). With a multitude of different interpretations in between, the same contrast arrived at the last century. Until the end of the last century (70's), the positive reductionist thinking has prevailed, and the hydrological cycle was considered purely in terms of simplified representations of mechanical interactions between the components of a watershed that can be controlled by humans. The increasing awareness of the complexity of managing water due to its multiple roles in the environment, revealed that classical engineering approaches could not always be the answer to safeguard human development. This allowed the emergence of a systems thinking perspective focusing on nature as a whole and on the importance of preserving all its components as a fundamental block of the natural dynamic equilibrium (Capra, 1994; Jørgensen et al., 2011).

Different theories (especially in economics) have been elaborated in the last decades promoting new paradigms of development (Costanza, 1992; Raworth, 2017). At the same time, also many natural resource management approaches have been proposed, trying to balance ecosystem and society (Grumbine, 1994; Cairns Jr; 1996 Tharme, 2003)

The so-called nexus approach goes in this direction, trying to move from a single sector optimization approach, where a natural resource is managed to maximize the revenue, to a more integrated view, where every resource is part of a bigger (eco)system made of connections that need to be managed as a whole. The concept of nexus is usually described as water-energy-food nexus (SEI, 2011) as water, energy and food represent the pillars of global security (Fig. 1.3). More generally, the nexus focuses on the ecosystem, stressing the importance of considering the connection among natural resources to preserve ecosystem equilibrium.

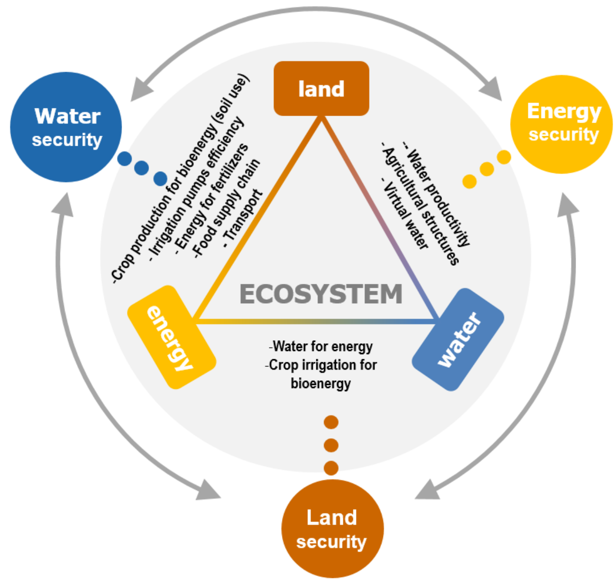

Fig. 1.3 Water-energy-food-nexus: The nexus perspective emphasizes the importance of understanding the multiple roles of resources, such as water, in a system. In fact, within the ecosystems, the intricate web of connections between different resources is the fundamental structure that needs to be properly evaluated, if we aim at improving the security and stability of the system.

Previously, environmental scientists and practitioners have used different terminology such as 'integrated resources management' or, as already mentioned, 'systems thinking' (Hayes and Crilly, 2014) emphasizing the importance of a holistic approach to achieve environmental protection and safety of societal development. Sustainable water-land-energy management and the characterization of all processes involved are directly connected with the definition of sustainability. Despite hundreds of definitions, the meaning of sustainability and how to effectively promote it in a holistic approach is still under debate (Beck and Walker, 2013). Similarly, the definition of nexus itself does not provide a clear view on how to approach the problem and might appear as a combination of ambiguous meanings and strong normative resonance (Cairns and Krzywoszynska, 2016). Even if the concept of nexus might be seen as the umpteenth buzzword, the importance of integration and transdisciplinarity remains unchanged and often unfulfilled. Therefore a “nexus approach”, meaning a multiscale and transdisciplinary systems thinking for the management of water, food and energy resources, represents the possibility of making a fundamental step forward in water management analyzing water issues in order to determine adequate solutions.

1.4. Enlarging perspectives: holistic approaches in water management

Before exploring the implications that the nexus framework has on water management, I briefly trace the history of the "Integrated Water Resources Management" (IWRM) concept. Then, I compare the IWRM and nexus approaches to better identify the differences and potential synergies among the two.

IWRM evolution

As already depicted in the background section, the necessity of coping with increasing water needs while assuring the sustainability of the development has posed major challenges in water management. According to Savenije and van der Zaag (2008) the peculiar nature of water implies that its management has to consider the following four dimensions: water resources (i.e. natural dimension), water users (i.e. human dimension), the spatial scale, and the temporal scale.

Recognizing the four dimensions of water resources as well as the inter-connectedness of both biotic and abiotic components of water resource systems represent the challenge for its management. Gourbesville (2008) summarizes these challenges as:

- the necessity to overcome the traditional infrastructure/management dichotomy and trying to take advantage in their complementary roles in contributing to sustainable growth and poverty reduction;
- the need of different scales of the water challenges moving from simultaneously being just a local issue to be a national and an international issue;
- the necessity of trying to use water as a catalyst of cooperation, instead of a source of conflicts; and finally
- the necessity of exploring innovative management frameworks that mix public and private efforts.

The idea of IWRM was developed according to these needs (Van der Zaag, 2005). International awareness on the importance of water increased in the last decades of the last century together with the consensus about the need for integrated approaches. Only at the end of the 80s, water entered the international debate and, in 1992 the basis of IWRM was posed both at the UN Conference on Environment and Development (UNCED) in Rio de Janeiro as well as at the International Conference on Water and the Environment (ICWE) in Dublin.

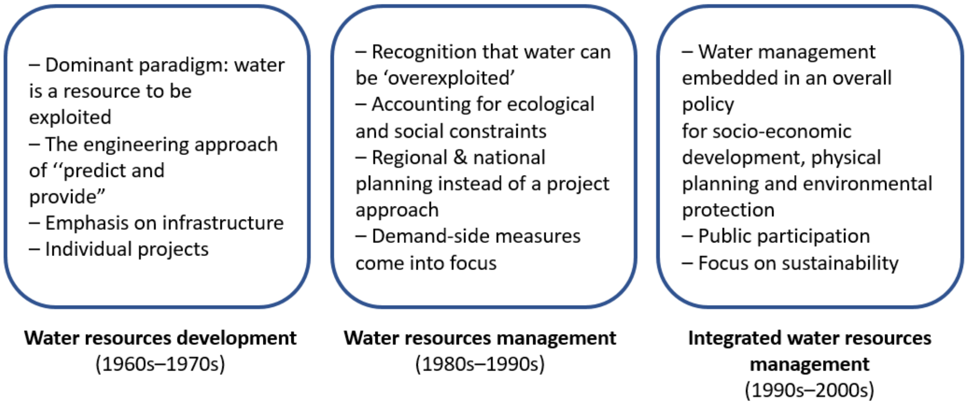

Fig. 1.4 Water resources development towards IWRM (adapted from Savenije and Van der Zaag, 2008)

The definition of IWRM that is most found in literature is formulated by the Global Water Partnership (2000), which defined IWRM as “*a process which promotes the coordinated development and management of water, land and related resources, to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*” (Fig. 1.4).

The IWRM definition and application has caused a huge debate among the scientific community. Starting from the Global Water Partnership definition, Biswa (2004) defined IWRM as a false innovation, underlying the vagueness of IWRM concept and its impossible applicability at the operational level. He also argued against the idea of seeking for integration claiming that what is needed is not integration in terms of management of two or more resources (that is not operationally feasible), but close collaboration, cooperation, and coordination between institutions that are in charge of managing these resources.

Several other academics have rebutted this criticism, explaining that IWRM represents a potential meeting point for water professionals and politicians. Mitchell (2004), answering Biswa's criticism, claimed that instead of a general critique on the concept “*what is needed is a systematic set of criteria against which IWRM should be assessed. Different assessors may advocate different criteria, but by making criteria explicit we are forced to make clear the basis on which IWRM is assessed*”.

Despite the obstacles for identifying operational ways to apply this concept and the disagreement on the final structure of the management framework, a common factor among these different visions of IWRM can be found in the fact that everyone is claiming for a more cooperative effort in managing natural resources.

In fact, the evolution of IWRM shows the shift from an approach considering mainly hydrological variables to a more integrated approach where environmental, economic and social aspects are included, the so called Integrated Land Water and Ecosystems Management. The central role of water in both ecosystems and society is highlighted and it is also the core of the so-called ecosociohydrology framework (Sivapalan, 2012)(Fig. 1.5).

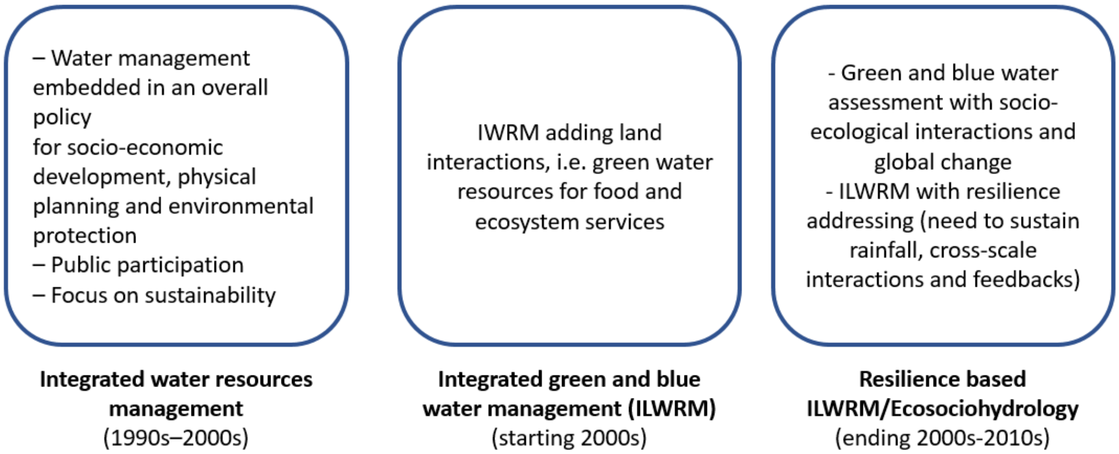

Fig. 1.5 Evolution of IWRM approaches to ecosociohydrology (adapted from Rockström et al., 2014)

IWRM and the nexus framework

As shown in the previous paragraphs, elements of the nexus approach are historically evident in water management: starting from the first river basin development plans and their formalization in the common framework of IWRM, concluding with the European Water Framework directive (WFD 2000/60/EC, Benson et al., 2015), all the developed management frameworks contain elements of integration that are similar to the concept of nexus. As defined by Savenije and van der Zaag (2008), integrated water resources management, seeks to manage water resources in a comprehensive and holistic way. IWRM therefore has to consider water resources from a number of different perspectives or dimensions. The nexus idea enlarges this view and embraces multiple dimensions of natural resources management, trying to define a common language that can help promoting a dialogue between different nature components that were previously considered independent.

In this sense, nexus can be seen as being evolved from IWRM. As shown by Benson et al. (2015), IWRM and nexus approaches appear closely related in terms of ultimate objectives (i.e. better resource use to allow for sustainable development of society) but they differ in certain aspects. Confronting the two approaches with critical indicators, Benson et al. (2015) came up with the definition of the key features of nexus and IWRM approaches (Tab. 1.1)

Tab. 1.1 Nexus and IWRM comparison (Benson et al., 2015)

	Nexus	IWRM
Integration	Integrating water, energy and food policy objectives	Integrating water with other policy objectives
Optimal governance	Integrated policy solutions Multi-tiered institutions	'Good governance' principles
Scale	Multiple scales	River-basin scale
Participation	Public-private partnerships – multi-stakeholder platforms for increasing stakeholder collaboration	Stakeholder involvement in decision-making Multiple actors, including women
Resource use	Economically rational decision-making Cost recovery	Efficient allocations Cost recovery Equitable access
Sustainable development	Securitisation of resources	Demand management

Focusing on the most significant differences, the nexus approach promotes a higher level of integration, where water, energy, food and more generally ecosystem security are equally important, while IWRM applies a water-centric view linking all the other sectors to water management. Nexus aims at an integrated policy solution, but is still lacking normative principles on the governance, while IWRM comprehends “good governance principles” such as transparency, collaborative decision-making and the use of specific policy instruments. The two approaches also differ with respect to the scales: nexus focuses on a range of scales of analysis for integrating multiple policy sectors, while IWRM has its natural reference scale in the hydrologically defined catchment scale.

In terms of participation, the nexus approach focuses more on the development of public-private partnerships as an important facilitating mechanism that can promote new investments. In IWRM, participation is defined as the identification and involvement of all the stakeholders to guarantee the provision, management and safeguarding of water resources. Regarding the vision on resources use, the approaches again differ. Both concepts refer to efficient resource use, but nexus in terms of economically rational decision-making, while IWRM in terms of optimization of water supply given efficiency, water pricing and demand management constraints. Also, the view on sustainable development differs: IWRM envisions it as demand management and resources preservation, while nexus introduces the concept of water security where water is "first amongst equals" in relation with food, energy, climate, economic growth, and human security challenges (ibid.).

Many general frameworks have been developed to explore the nexus at different scales (Bazilian et al. 2011; Lawford et al. 2013; Ringler et al. 2013). Among the most frequent concepts associated with nexus framework are the ideas of adaptation (Scott et al., 2015), risk (Gafney et al. 2012) and multiple resources security (Bizikova, 2013). The challenge is to take advantages of the possible synergies among the different approaches for promoting a more comprehensive watershed management.

1.5. Mixing languages

The previous paragraphs have shown the emergence of the concept of nexus, the evolution of IWRM and a comparison among the two. The inherent objective of the thesis is to link the different perspectives presented, translating the general nexus approach into operative tools that can support watershed management. As already stated in the introduction, this thesis is starting from three main concepts that are hereby contextualized: ecosociohydrology, ecosystem services and water accounting. The objective is to give new interpretation to existing languages and integrating their peculiarities to create analysis framework useful to deal with nexus issues.

Ecosociohydrology

Ecosociohydrology might be considered as the last step in IWRM evolution that focuses on the interactions between natural and human forcing, understanding hydrological systems as a changing interface between environment and society (Sivapalan 2012, Montanari et al., 2015). Water partitioning (green and blue water flows), cross scale interactions and feedbacks are the key aspects to be investigated. Moreover, the role of society as a driver of change and as an element of the system that react with transformation and adaptation to the changes, appears a fundamental aspect to achieve social and ecological resilience (Fig. 1.6, Rockström et al, 2014).

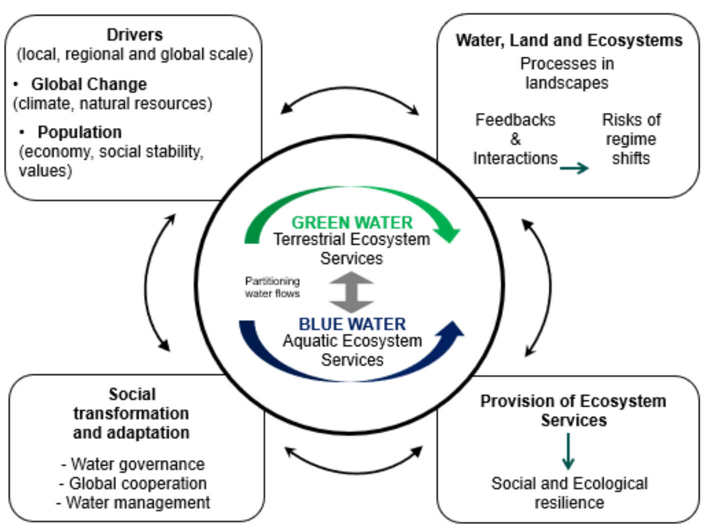

Fig. 1.6 Interconnection within a water socio-ecological system (adapted from Rockström et al., 2014). The scheme highlights the importance of analyzing the different drivers affecting the green/blue water partitioning and determining the interrelationships between human well-being and ecosystems.

The idea of coupling the analysis of hydrological systems with the eco-social system is now the core of IWRM evolution. Therefore, IWRM should address hydrological challenges while preserving ecological processes, which are considered essential for biodiversity preservation, ecosystem functioning and the provisioning of ecosystem goods and services. However, this view has not been properly developed in IWRM yet. For example, Jewitt (2002), analyzing the existing approaches to the implementation of IWRM, pointed out how aquatic ecosystems are often "*considered amongst the important users of water, but this tends to divert attention from their role as providers of water resources and other goods and services, with the result that limited recognition is given to the critical importance of these as a basic element of IWRM*". Considering that growth and development should be complementary, rather than antagonistic to environmental protection, Jewitt (2002) explained that the maintenance of ecosystem functioning should be seen as a fundamental component of water management (D'Odorico et al., 2010).

Ecosystem services

The nexus framework can be seen as an approach that aims at the maintenance of ecosystem integrity, i.e. the term most often used as a measure of ''wholeness'' and ability to continue to function in a natural way (De Leo and Levin, 1997).

An ecosystem is made of living and non-living components that interact as complex dynamic systems, of which humans are an integral part (MEA 2005). Ecosystem are characterized by certain functions that produce services to humans, the so-called ecosystem services. The origins of the ecosystem services (ES) theory date back to the late 1970s (Ehrlich & Ehrilch, 1981; Mooney et al., 1994), but the scientific community came up with a shared definition only in recent years (Braat and De Groot, 2012), especially with the publication of the Millennium Ecosystem Assessment (MEA) in 2005. Ecosystem services can be defined as the conditions and processes through which ecosystems, and the species that make them up, sustain and fulfill human life (MEA, 2005).

ES are usually represented as a flow from a stock of natural capital. Services seem to flow effortlessly from ecosystems to beneficiaries, but the reality is that they require appropriate management to assure their production and human effort to be transported and distributed. According to Spangenberg et al. (2014), it is useful to differentiate between ecosystem function (ESF), potential ecosystem services (ESP) and ecosystem services (ES). In their work, ESF are the biogeochemical characteristics of ecosystems, including structures and processes that are entirely a part of the ecosphere. ESP are the potential ecosystem services that can be derived from an ecological process and constitute an overlap of the bio- and the anthroposphere. Different use values can be attributed to the same ESF and it is a matter of human needs and social demands to give a "*new meaning to what was beforehand nothing but a piece of managed or unmanaged nature*" (ibidem).

It is therefore evident that we need to differentiate between places where the function is generated (and that can be investigated with analytical methods), and the places where this function is converted to a service, i.e. the areas, where there is a demand for services recognized as such and subjectively valued by humans (Fisher et al. 2009). This has important implications for watershed management, because it highlights the importance of the connections between nature and society and delineates the possibility of implementing an approach of analysis that is suitable for the nexus concept.

The ES concept provides a holistic approach for framing socio-ecological issues and for integrating different biophysical and socio-economic data and represents an effective way to give an operational interpretation to the concept of integration. Water, food and energy are components of an ecosystem, and they can be considered as “services” that ecosystems produce for human wellbeing. According to the Millennium Ecosystem Assessment (MEA, 2005) we can distinguish four different classes of ecosystem services: provisioning, regulating, supporting and cultural. Water supply, food and energy production are all different examples of provisioning services, i.e. “services” underpinned by ecosystems for human demand.

Within the hydrological cycle, water and land interactions determine the ESF that can produce different potential services from all the three classes identified. In fact, water ESF (i.e., the ecohydrological process) creates the ESP and then the human needs determine the flow of ES in the watershed.

A wise water management should aim at increasing the benefits gained by society from the ES provided by harvested resources and preserving the ecosystem itself to assure the future provision of ES (i.e. sustainability). As already stated, ES do not flow effortlessly from ecosystems to beneficiaries; the production of an ES is the result of the interactions between humans and nature. The effects of ecosystem modification on ESF and thus on ES must be assessed to achieve a sustainable management that aims at the maximization of the total long-term benefits (Jewitt, 2002, Fig. 1.7).

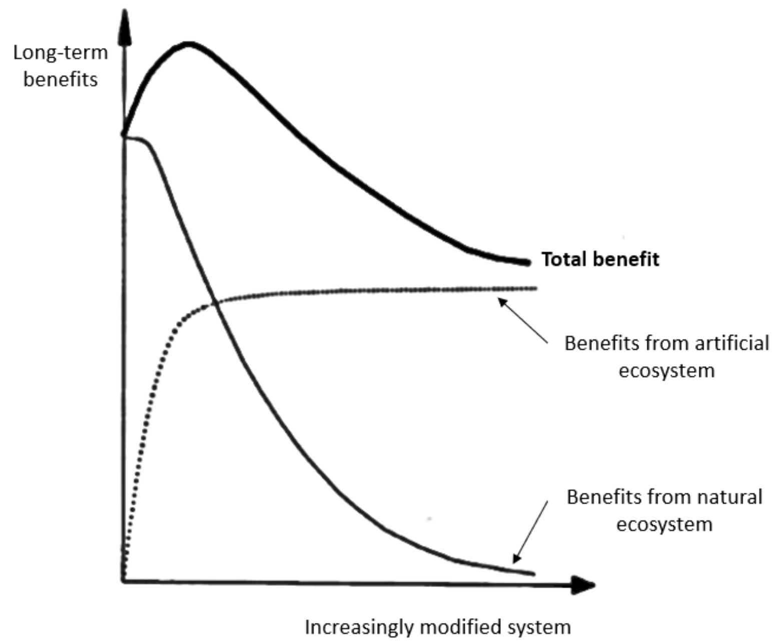

Fig. 1.7 The graph shows the quantity of ecosystem services derived from a system (Jewitt, 2002). Modifying the system decreases the benefit associated to natural ecosystem (e.g. supporting habitats), while increasing the artificial services (e.g. water supply). Ecosystem management should aim at maximizing the total long-term benefits whilst conserving choice opportunities for future generations.

Water accounting and water footprint

Solving water problems requires information from many disciplines, and the physical account (describing sources and uses of water) is a fundamental component (Kuiper et al., 2010). In fact, water accounting, meaning providing consistent and coherent information on water resources and the services generated from consumptive use in a geographical domain, is an essential step to determine the actual state of a water system and to provide a reference point for future benchmarking.

In this context, water footprint analysis represents a fundamental tool to derive detailed information regarding water use. The Water Footprint (WF) concept was introduced by Hoekstra and Hung (2002) when they were looking for an indicator that could map the impact of human consumption on global fresh water resources. It refers to all forms of freshwater use (consumption and pollution) that contribute to the production of goods and services consumed by the inhabitants of a certain geographical region (Hoekstra & Chapagain, 2008). The concept of the WF is closely linked to the virtual water concept, introduced by Allan (1997): virtual water is defined as the volume of water required to produce a commodity or service. In terms of scales of analysis, the concept of virtual water and water footprint are strongly connected the concept of globalization of water where every catchment is connected to the rest of the world through fluxes of other resources, such as, for example, food. At the same time, global water issues are very locally dependent, especially when water management is the main concern. Therefore, water management issues can be seen as glocalization effects (Bauman, 1998) where every action that is taken by water managers should consider local/global interdependent scales of effects (i.e. moving toward the idea of nexus).

Starting from the virtual water definition, Hoekstra and Hung (2002) defined the WF as an indicator of direct and indirect freshwater use. Water use is measured in terms of consumed water volumes (evaporated or incorporated into a product) and/or polluted per unit of time. The method defined by Hoekstra et al. (2011) in the WF assessment manual, is composed by a four-step approach, including (i) setting goals and scope, (ii) water footprint accounting, (iii) sustainability assessment, and (iv) response formulation. The accounting phase includes the quantification and mapping of freshwater use with three distinct types of water use: blue water, defined as the fresh surface or groundwater use; greywater, related to water pollution; and green water, defined as the rainwater that does not become runoff (Hoekstra et al., 2011).

WF methodology has also been developed within the Life Cycle Assessment (LCA) community, resulting in a dedicate ISO (ISO 14046, 2014) reflecting the conceptual structure of Life Cycle Assessment (ISO 14044, 2006): goal and scope definition, inventory analysis, impacts assessment, and interpretation (Fig. 1.8).

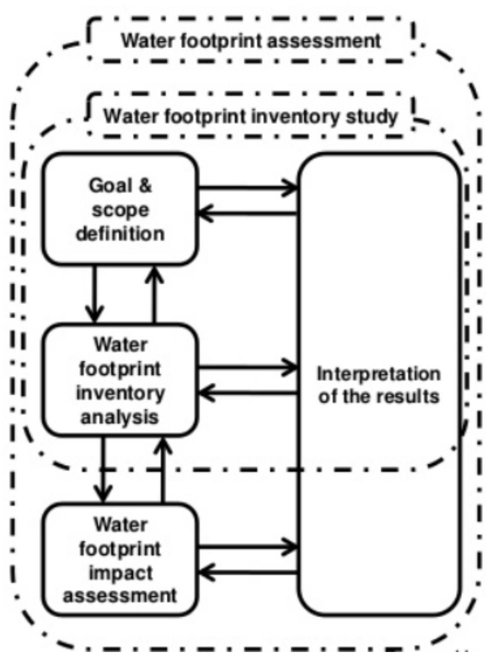

Fig. 1.8 Conceptual framework of the water footprint approach according to life cycle assessment (ISO 14046). First step of is the identification of the boundaries of the system analyzed. After the definition of the goal and scope of the analysis, the inventory of all the fluxes of water in the system is realized. Finally, the impact related to water use and pollution are assessed. All the phases are associated to the interpretation of the results that can lead to several iterations of the procedure.

LCA and WF methodologies again emphasize the importance of integration (Pacetti et al., 2015), showing that a comprehensive assessment of resource use within the life cycle cannot be completed without taking water into account. Therefore, the WF can be considered an important improvement to the classical LCA methodology. Moreover, the WF can take advantage of the LCA, integrating water assessment with other environmental indicators that can promote an understanding of the real impacts on the analyzed system (Boulay et al., 2013). The use of footprint indicators, and in particular of WF, can lead to a more sustainable water management, providing detailed information regarding water use and setting a benchmark to increase water efficiency performances of critical sectors.

1.6. Implication for the thesis

My thesis develops the idea of interpreting the water management from the perspective of the water-land-ecosystem nexus.

I identified three concepts that can support the implementation of a nexus-based approach in watershed management (Bakker, 2012): ecosociohydrology, ecosystem services, water footprint. Ecosociohydrology theory allows the interpretation of a hydrological systems as a changing interface between environment and society (Sivapalan et al.,2012). Ecosystem services provide a holistic approach for framing socio-ecological issues and for integrating biophysical and socio-economic data (De Groot et al., 2002). Water Footprint, and more generally water accounting, support the better understanding of the current state of water resources, as well as future challenges and opportunities for improvements of water use in a particular area (Chapagain & Orr, 2009). In the thesis these three concepts are jointly explored to build operative approaches to support watershed management.

From this point of view, managing water resources becomes a broader discipline that involves not only the actions needed to maintain water quantity and quality, but also aims at maximizing the overall amount of services derived from water, while preserving the environment, thus securing the ecosystem functions.

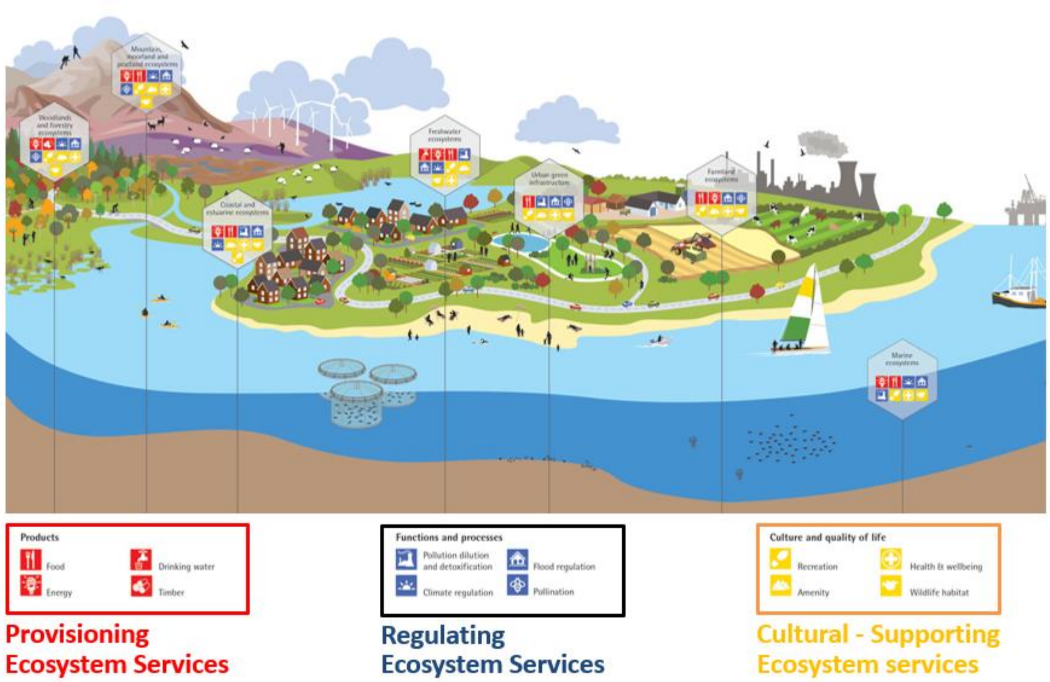

Fig. 1.9 Water-related ecosystem services overview. According to the Millennium Ecosystem Assessment (MEA, 2005), four classes of services related to water are defined: provisioning services (such as drinking water, food production, etc.), regulating services (such as flood regulation or climate regulation), cultural services (such as amenities or recreation) and supporting services (such as the support of vital estuaries and other habitats).

Water - flowing in a landscape and interacting with terrestrial ecosystems - provides a large set of potential ecosystem services (Fig. 1.9). These services are a function of human-environment interactions that influence the ecosystem and its functioning. Watershed management, therefore, should be thought in relation to the ecosystem functions and considering how land-water management decisions could affect them. This information is fundamental to develop proper management strategies, in particular to improve the understanding of how the human-environment interactions may influence the quantity and distribution of the services associated with water resources.

In Fig. 1.10 a general investigation framework is outlined as a reference rationale to deal with nexus issues in water management.

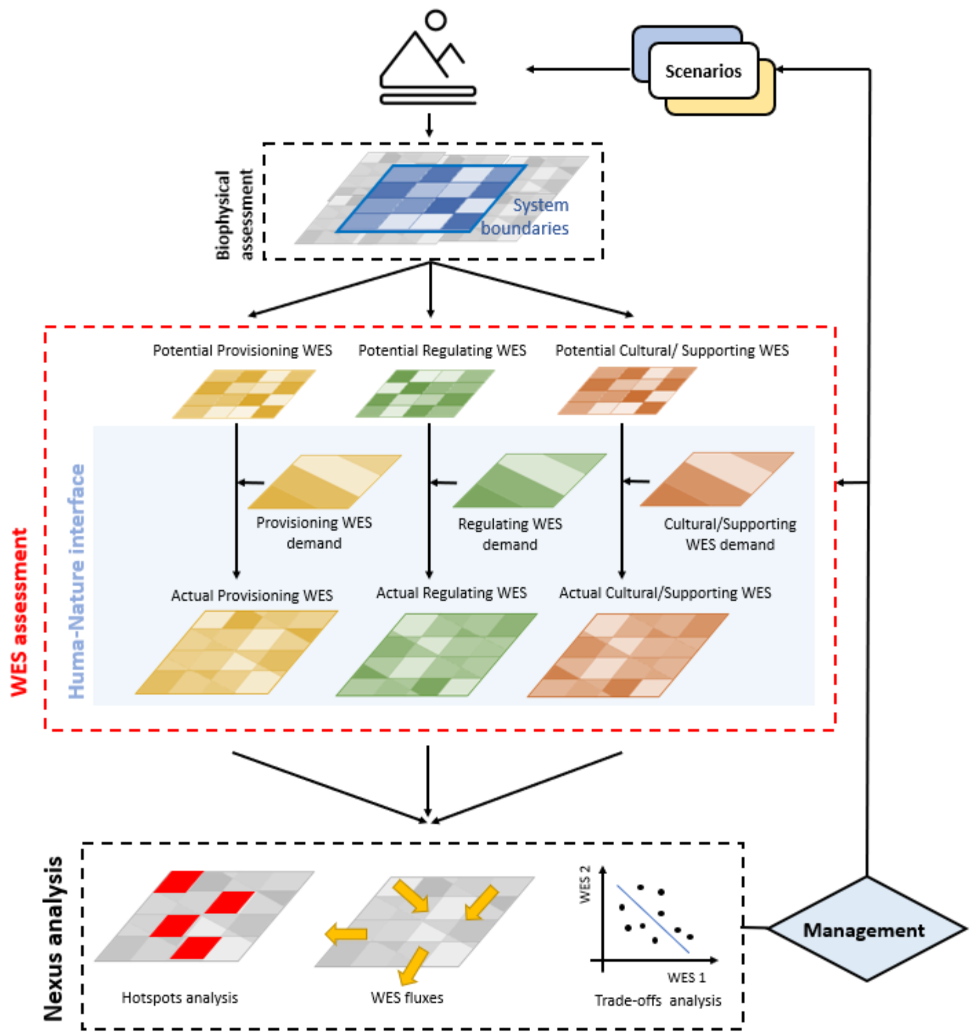

Fig. 1.10 Water management within the water-land-ecosystem nexus. The scheme depicts the rationale behind the different case studies. Based on a biophysical assessment of water resources the potential water-related ecosystem services (WES) are estimated. The evaluation WES demand provides information regarding the conversion into effective WES and allows analyzing associated risks and benefits. The analysis of the nexus between different WES is then possible to derive management strategies and development scenarios that can act at the landscape level or at the demand level.

Starting from the biophysical processes that characterize a watershed, by means of hydrological modelling (as in chapter 2 and 3) or remote sensed information (as in chapter 5) we can identify the WES potential (e.g. water availability can be interpreted as the presence of potential provisioning service). Analyzing the demand of WES associated to the human component of the system (chapter 4) is then possible to define the distribution of the actual WES and to identify the associated hotspots.

The analysis of WES multiple presence in a territory can give useful insights on the WES co-occurrences and on their relationships (i.e. the nexus). The information derived from such a framework of analysis support water management decision making that can act both at the landscape level, modifying the territory to increase certain types of WES production (e.g. changing land use to increase flood regulation), or at the demand level, acting on the WES demand (e.g. acting on the WF to reduce provisioning WES demand).

With respect to the overall research questions delineated in the introduction, the literature review yields the following implications:

- How can water management benefit from the **nexus concept**?

The Antrophocene and its multiple pressures on limited resources require a higher level of integration to bring human development back to safe and fair boundaries. Water represents a key resource and, due to its high connectivity, it plays a fundamental role within the nexus. This role needs to be investigated to improve existing water management and to develop a broader transdisciplinary perspective. This implies that water management should focus on the role of water in relation with the ecosystem of which is part, framing water management decision making in relation to the overall effect on the water-land system.

- What are the **scales of analysis**?

The water-land-ecosystem nexus is characterized by increasing level of complexity at different scales of analysis. Dealing with water resources from a nexus perspective means to look at the overall behavior of the land-water system that is determined by the combination of multiple human-nature interactions and is linked to the ecosystem spatial heterogeneity. From this perspective, the catchment scale usually adopted as the reference scale in water management becomes a control volume where to investigate nature-human interactions that act at different spatial and temporal scales. For example, the flow regulation service at a certain location is the function of all the processes that occurred before in the upstream area. Moreover, it is also influenced by policies that have been developed at a larger spatial scale, usually national (e.g. agricultural policies that determine a land use change or energy policies that determine the construction of a hydropower plant).

In the thesis three different case studies have been analyzed to develop tailored assessment procedures that could deal with the different levels of integration and scales within the nexus. Each case study is defined as a combination of scale, level of integration and context (Fig. 1.11).

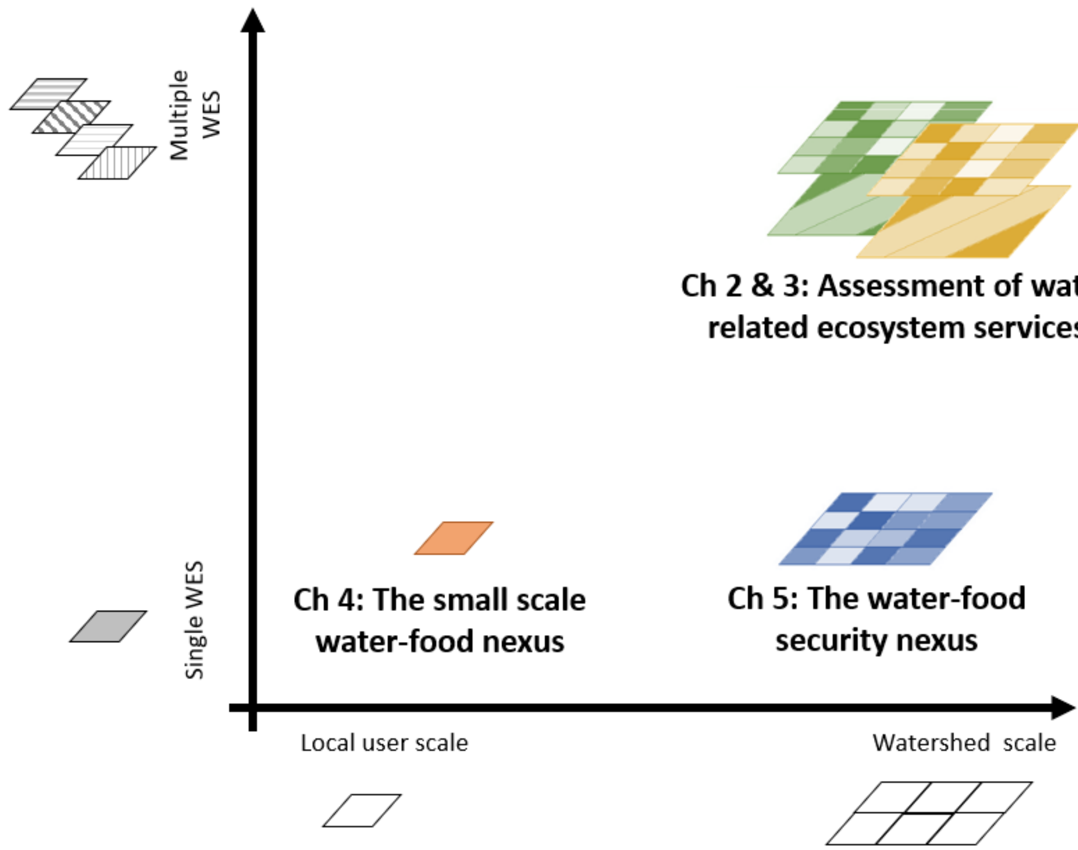

Fig. 1.11 Scheme of case studies classified according to the reference scale of analysis (x-axis) and the level of connectivity (y-axis). Chapters 2 & 3 contain an assessment of multiple WES at the basin scale, chapter 4 focuses on farm scale considering only food production. Chapter 5 contains the analysis the water-food nexus focusing on food production at the basin scale.

- How can the nexus concept be translated into an **operative framework** of analysis?

Managing water resources means to deal with a high spatial heterogeneity of landscapes and processes that imply the adoption of a multiple scale approach. There is a need of an integrated approach both in terms of biophysical assessment of the variables that describe the water system and in terms of the evaluation of the multiple effects of decision making. From a nexus perspective, managing water resource is a multi-scale integrated assessment of the risk and benefits associated to a land-water system. In chapters 2 and 3, I adopt the watershed scale to develop an analysis of the multiple WES, using hydrological modelling and water accounting to highlight the hotspots and co-occurrences of provisioning and regulating WES. In chapter 4, I use WF accounting methodologies to quantify the demand of a WES provisioning services (i.e water supply) at the farm scale. In chapter 5, integrating remote sensing data and food production statistics I quantify the effects of flood (i.e. lack of regulating WES) on food security of two developing countries, highlighting the different water-land nexus in each case study.

2

Assessment of water-related ecosystem services to support the Arno river basin management

2.1. An ecosystem perspective to deal with water-land nexus

As highlighted in chapter 1, Ecosystem Services (ES) represent a useful perspective to explore the complexity of water-land connections. Ecosystem services are defined as the conditions and processes through which ecosystems sustain and fulfill human life (MEA, 2005). Water-related ecosystem services (WES) are, specifically, the multiple benefits produced by the interactions between terrestrial ecosystems and freshwater as it moves through the landscape (Duku et al., 2015). Terrestrial ecosystems in a watershed affect the attributes (e.g. quantity, quality, spatial and temporal variability) of the water that passes through it, meaning that every ecohydrological process determines potential ecosystem services that can be used. WES constitute an overlap of the biosphere and the anthroposphere (Spangenberg et al. 2014): the presence of recipients (e.g. water users) as well as spatiotemporal water availability determine the shift from an ecohydrological process to a WES. According to Braumann (2007), WES can be categorized into four classes: 1. provisioning WES that include the improvement of extractive water supply and in-stream water supply; 2. regulating WES such as water damage mitigation; 3. cultural WES that are related to the provision of religious, educational and tourism values; 4. supporting WES such as the support of vital estuaries and other habitats.

WES assessment is a promising methodology for integrated basin management strategies, thereby to investigate how water could be better allocated and to produce multiple WES without compromising the ecosystem. With the recent expansion of the field of ES assessment (Seppelt et al., 2011), a number of tools are available for ES assessment (e.g. Bagstad et al., 2013). Focusing on WES, hydrological models represent a convenient choice to deal with the complexity of all the ecohydrological processes from which WES derive (Vigerstol et al., 2011). Hydrological modelling provides a quantitative basis for the biophysical evaluation of the ecosystem potential capacity to produce WES and, coupled with water accounting (Molden and Sakthivadivel, 1999), it provides insights into the conversion of ecohydrological processes to a human benefit.

In this case study, the Soil Water Assessment Tool (SWAT, Arnold et al., 1998) is used. Although a systematic approach for WES estimation and evaluation of their fluxes with SWAT is still missing (Francesconi et al., 2016), the model is suitable for developing a WES assessment. SWAT assures an accurate quantitative, spatially explicit estimate of all hydrological attributes, such as evapotranspiration or runoff, whose knowledge is crucial for assessing WES. On this basis, SWAT is a suitable tool for scenario analysis of interventions on smaller scales (e.g. subbasin or reach scale). SWAT output can be used interchangeably to make diverse assessments of WES, in particular to model regulating and provisioning services (Karubulut et al., 2016; Schmalz et al., 2016). SWAT is more data intensive but provides the detailed scale of analysis that is missing in simplified modelling approaches working at larger spatial and temporal scales (Dennedy-Frank, 2016).

The scope of this study is the spatially explicit quantification of WES in the upstream part of the Arno river basin to figure out the connections of water with other sectors such as food and energy production, and its multiple role in regulating the watershed behavior. The hotspots associated to the different WES and the trade-offs and synergies among different services are identified.

The analysis is based on the integration of hydrological modelling and water accounting. On one hand, water accounting represents the basis for sustainable allocation, allowing the identification of WES demand; on the other hand, the integration with the ecohydrological modelling helps clarifying the processes on which WES production is based. The selected case study focuses on surface water because of its recognized importance in the area and the relevance of the associated management problems (the share of surface water on the total water use is around 80 % according to Autorità di Bacino del Fiume Arno, 2010).

Despite an increasing number of emerging conflicts among users, current information on water allocation and other WES in the Arno basin remains scarce. An ecosystem-based approach is fundamental to effectively evaluate the complexity of the interconnections between the different WES produced by water within the basin and to link it to the existing management and regulating framework, such as the Water Framework Directive (WFD). The WES concept is strategic for the implementation of the WFD that looks at the protection of ecosystems to preserve long-term availability of water resources and to assure the benefits deriving from aquatic ecosystems. Despite WES are not mentioned directly in the WFD, its implementation could take advantage of the WES concept to highlight the human-nature relationships and to promote multi-functional measures and more efficient solutions (Grizzetti et al., 2016).

The analysis framework follows these steps: (i) definition of the major challenges regarding water management in the basin; (ii) hydrological modelling and water accounting to evaluate the hydrological behavior and the water use in the basin; (iii) spatially explicit simulation of provisioning and regulating WES; (iv) evaluation of hotspots (both from hydrological and ES perspectives) and analysis of ES trade-offs.

2.2. Materials and methods

Case study

The catchment considered for this analysis is the upper part of the Arno basin, upstream of La Penna dam (N 43°54'56'' E 11°29'48'', N 42°54'37'' E 12°12'21'', Tuscany, Italy). It is divided into three main sub-catchments, Casentino, Val di Chiana and Valdarno Superiore, with a total area of 2,227 km^2 (Fig.1).

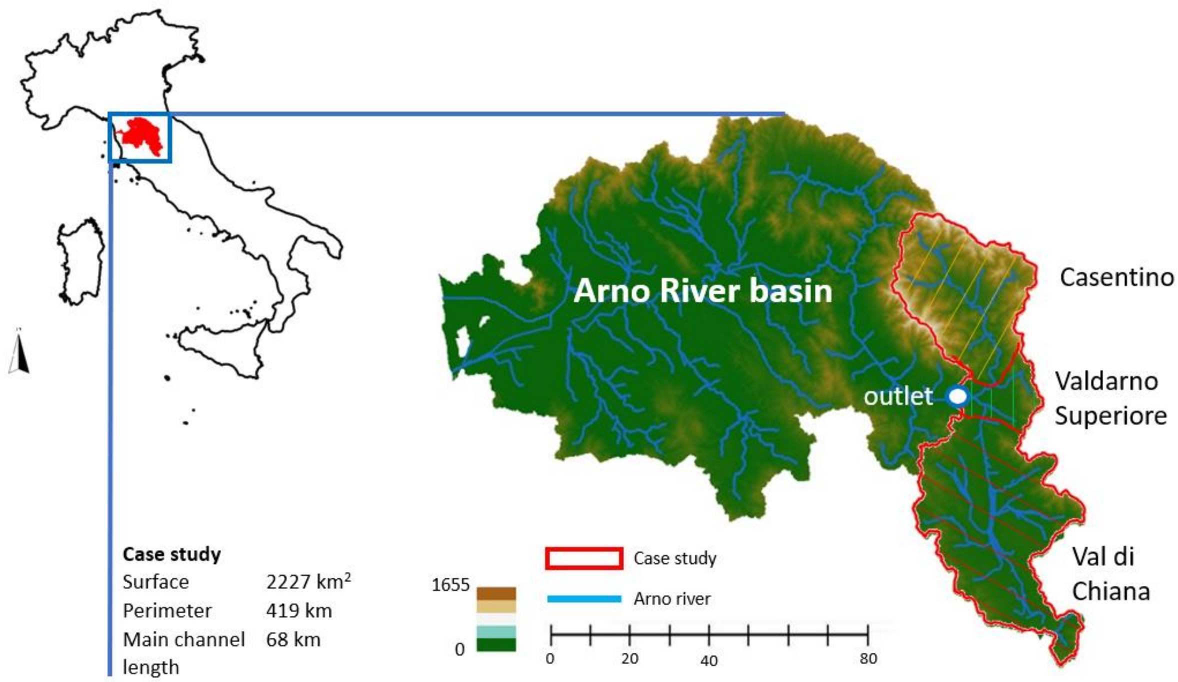

Fig. 2.1 The entire Arno river basin with highlighted the sub-catchments serving as research area.

Arno River originates from the southern slope of the Falterona Mountain (1385 m a.s.l.) flowing in northwest – southeast direction through the Casentino area. Here the territory is mostly mountainous with presence of hilly areas as a connection with the downstream valley. After crossing Casentino area, the Arno River flows in the Arezzo plain (Valdarno Superiore). Near the western edge of the plain, 60 km from the source, it joins the Chiana channel, an artificial channel of the land reclamation area of Val di Chiana, which flows in south-north direction. Val di Chiana, in contrast with Casentino, is characterized by wider and mostly flat spaces. The climate of the area is Mediterranean with average maximum and minimum temperature of 28.5 °C and 12.6 °C in summer and 8.5 °C and 1 °C in winter, respectively. The mean annual precipitation is 946 mm (period 2003-2013). Soils are characterized by a large variety (145 classes) with a predominance of *Umbric acrisols (silt loam soil)*, *Calcaric Cambisols (calcareous loam soil) and Dystric Endoskeletic Cambisols (clay loam soil)*. Land use in the basin is manly forest and cropland (36%

and 26%, respectively), with a 5% of olives trees. Irrigated agriculture represents a minor share (12%) of the total cultivated land, but is relevant in Val di Chiana area.

Around 290,000 inhabitants live in the case study area (20% in Casentino and 80% in Val di Chiana and Valdarno superiore). The economy of Casentino has been heavily transformed from the beginning of the 20th century. The development of industrial activities (especially textile industries) contributed to progressively shift the settling downstream, weakening the links of population with the hill systems and mountain areas. Currently, the water-intensive textile manufacturing industry is declining and an unsupervised development of residential and agricultural activities as well as other industrial sparse areas has characterized the lower Casentino area, which is prone to hydrogeological risk. The hydrogeological risk is exacerbated by the progressive state of forest abandonment in the mountains and the upper hilly areas.

Similarly, Val di Chiana has faced an increasing state of abandonment of the hilly areas with population moving to the agricultural areas of the valley. In fact, after the land reclamation works made during the first decades of 20^{th} century, Val di Chiana area is one of the most fertile agricultural areas in Italy and the local population is largely devoted to the primary sector. Due to the abundance of water, industrialized agriculture is highly developed in the valley and includes both irrigated (monocultivation of cereals and fodder for breeding, sugar beet, tobacco, nurseries and orchards) and rainfed agriculture (as viticulture and olive cultivation). This has caused increasing pressure on water resources in terms of quantity and quality.

Valdarno superiore is characterized by an ancient industrialization and now has an active and differentiated economy with food, textiles, clothing, footwear, mining, chemical, metalworking and electromechanical sectors. This has caused critical processes of urbanization and consumption of agricultural land often associated with the dense network of road infrastructure.

Methods

(i) Linking WFD with WES: defining the major challenges regarding water management in the basin

An overview, based on local knowledge, on the case study characteristics and criticalities is crucial to implement an effective evaluation of the complexity of the WES produced in a basin. By closely collaborating with the Arno River Basin Authority (RBA), the main issues related to water management, as well as the WES to be assessed have been defined, based on the water management plan of the Appenino Centrale District (i.e. the second cycle of the WFD implementation in the area according to Autorità di Bacino del Fiume Arno, 2016). Linking the actual WFD-based management plan, that represents the main reference for the status of water resources in the area, with the concept of WES provides an alternative key for interpreting the plan itself. Adopting an ecosystem services-based approach within the EU WDF implementation allows for (i) conceptualizing the link between humans and environment, and (ii) aiming at an a balance between the use of natural resources and the maintenance of the ecosystem functions (Blackstock et al.2015). In particular, an ecosystem services-based approach can support the WFD in promoting wider policy objectives of sustainability, moving the focus from good ecological status to the importance of showing how the ecosystem supports societal goals. This represents an important change of perspective: WFD is based on the classical DPSIR (Driver, Pressure, State, Impact, Response) approach (Borja et al. 2006), where the human-nature relationship is analyzed in terms of impacts. An ecosystem services-based approach moves towards a more proactive approach, where attention is posed on the socio-ecological process from which impacts are generated (Kelble et al., 2013). At an operative level, WFD-derived plans contain valuable information to introduce the WES concept within river management, providing basin-wide information regarding drivers of pressures and magnitude of their impact. The analysis hereby proposed gives a new interpretation of the water management plan of the Appenino Centrale District where impacts on water resources are interpreted in terms of WES. For example, a high level of pressure of agriculture on water resources can be interpeted as WES demand exceeding local WES availability. Therefore, the water management solutions should act on the entire socio-ecological system both to enhance the WES that environment can produce or to lower the levels of specific WES demand, aiming at the maximization of the overall WES production in the system.

A preliminary evaluation of the main challenges in the basin is carried out using the indicators adopted by the local RBA. The level of impact due to the distributed pressures associated with agriculture, industry and urban areas, is derived from the analysis of the share of areas allocated to each sector compared to the total surface available at the subbasin scale. For sediment and flow regulation, the level of criticality is assessed through the river functionality index (Siligardi et al., 2000) which gives information regarding the erosion and flow regulation in the basin. The information derived from these indicators is then converted into a common qualitative classification of the main challenges and provide the basis to determine the related WES to be quantified. This study focuses on the two main WES classes directly associated with ecohydrological processes in a basin, i.e. provisioning services (e.g. water supply) and regulating services (e.g. erosion regulation).

(ii) Ecohydrological modelling: SWAT (model set up and calibration)

The WES identified as crucial for the river basin can be linked to specific ecohydrological processes from which they derive. In fact, the WES provision is strongly related to ecohydrological processes that determine how precipitation is partitioned into two main water flows: green and blue water flows. Blue water resources are stored in aquifers, and lakes and generate flows in rivers, through wetlands, and through base flow from groundwater. Green water resources are stored as soil moisture and flow from terrestrial biomass (Falkenmark and Rockström, 2006).

Modelling ecohydrological processes such as the interaction between water and land (e.g. soil stabilization, water use by plants, surface flow path alteration) appears essential for determining the spatial and temporal variability of hydrological attribute, such as water quantity, water quality, location and timing). This information can be converted into potential WES and help identifying the areas for WES production.

The Soil Water Assessment Tools - SWAT (Arnold et al., 1998; Arnold and Fohrer, 2005) model is used to evaluate the blue and green water availability as well as soil erosion and other hydrological variables that can be used as WES indicators. SWAT is a semi-distributed eco-hydrological model suitable for modelling water quantity, water quality and soil erosion processes at the catchment scale. To quantify these processes, SWAT uses so-called Hydrological Response Units (HRU) as modeling unit, which are unique combinations of elevation, slope, land use, and soil types in the basin. Model results are then available at different levels of aggregation, starting from the HRU level up to the subbasin scale.
Table 1 summarizes the data inputs used to model the hydrological functioning of the basin. Land use data was derived from the Regione Toscana land cover dataset (Tuscany Region, 2017) that is a modified version of the Corine Land Cover dataset and contains four levels of classification including specific cultivation differentiation (e.g., olive and grape trees). Moreover, a dedicated level for irrigated agriculture was realized to properly model the spatial distribution of irrigated areas in the basin. Intersecting the information related to the irrigation abstraction in the basin (data provided by the Arno RBA) with the extension of irrigated areas provided by Italy's National Statistics Institute (ISTAT, 2010), the irrigated agricultural areas were identified as buffer of every abstraction point, assuming that each location serves an equal area of cultivation.

An official soil data set (Tuscany Region, 2017) provides soil texture information and the characterization of hydrologic soil group. Additional other soil parameters needed in SWAT are obtained through pedo-transfer functions based on soil texture information and hydrologic group classification (Saxton et al, 2006). Meteorological data are acquired by Tuscany Region Meteorological Database with a spatial distribution that is representative of the case study area (Fig. 2.2).

Tab. 2.1 Swat data model input, source and format.

SWAT model input	**Source**	**Format and Spatial/Temporal scale**
Elevation	Tuscany Region[1]	Grid 10 × 10 m^2
Soil	Tuscany Region[1]	Vector 1:10,000
Land use	Tuscany Region[1]	Vector 1:100,000
River network	Arno River Basin Authority[2]	Vector 1:25,000
Meteorological data	Regional Hydrological Service[3]	2005-2014 dataset (daily)

[1] Web Map Service (WMS) Geoscopio of the Tuscany Region (http://www.regione.toscana.it/-/geoscopio)
[2] Open Data, Arno River Basin Authority (http://www.adbarno.it/opendata/)
[3] Tuscany Region Meteorological Database (www.sir.toscana.it)

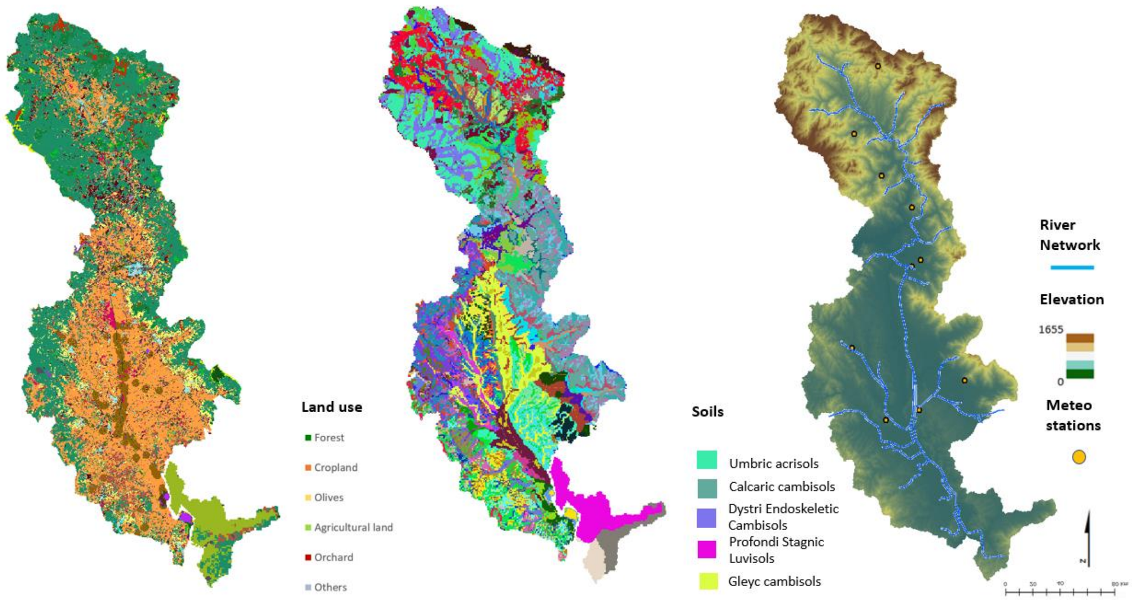

Fig. 2.2 Swat model input datasets

The number of HRU to be considered in the simulation phase is optimized through an analysis of Pareto-optimal threshold combinations (according to an approach developed by Strauch et al., 2016). The basin is subdivided into 54 subbasins corresponding to the tributaries to the main channel. The total number of HRU in this model is 981.

The conceptual basis of the SWAT model is a mass a balance following the equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} + Q_{surf} + E_a + W_{seep} + Q_{gw})$$

where, SW_t is the final soil water content (mm), SW_o is the initial soil water content on day *i* (mm), *t* is the time (days), R_{day} is the amount of precipitation on day *i* (mm), Q_{surf} is the amount of surface runoff on day *i* (mm), E_a is the amount of actual evapotranspiration on day *i* (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm), and Q_{gw} is the amount of return flow on day *i* (mm).

This equation is applied at HRU level. Every component of the mass balance can be divided in blue and green water fluxes and storages (Rodrigues et al. 2013). The evaluation of blue water availability is based on the *Water Yield* output provided by the model as a sum of surface, lateral and shallow aquifer contributions to streamflow. The amount of water yield represents the blue water flow, which contributes to the supply of most of the WES provisioning services. It is quantified for every subbasin or HRU on a monthly time step. The soil water content estimated by the model is then used to evaluate the green water availability and thus the potential green provisioning WES (Karubulut et al., 2015), while the actual evapotranspiration is representative of green water fluxes, i.e. the green WES demand. The evapotranspiration is estimated according to the method developed by Hargreaves and Samani (1985). Sediment yield for every subbasin is also calculated for every time step at the subbasin/HRU level. This allows for identifying the areas more prone to erosion. The sediment yield at the HRU scale is calculated using the Modified Universal Soil Loss Equation (Williams, 1975 a, b) as a function of the runoff and the characteristics of the soil, the K_{USLE} soil erodibility factor, the C_{USLE} cover and management factor, the P_{USLE} support practice factor, the LS_{USLE} topographic factor, and the C_F coarse fragment factor.

The simulation period is 2005-2014: data from the period 2005-2007 are used for the model warm up, the period 2008-2011 for the calibration and finally, the period 2012-2013 for the validation. The SWAT hydrological parameters are calibrated using SWAT CUP (Abbaspour, 2007) considering the three main sub-catchments within the case study area through a differentiated parameterization. Calibration and validation results are analyzed at the monthly time step. The model is evaluated considering different performance criteria, including the coefficient of determination (R^2), the Nash Sutcliffe efficiency (NSE), the ratio between the root mean square error and the standard deviation of measured data (RSR), and percent bias statistics (PBIAS).

(iii) Water accounting

Multiple water use characterizes this catchment. Water use estimation is therefore a key step to evaluate WES demand within the basin. In fact, water use represents the real quantification of the provisioning WES demand. Four main classes of water use are considered in this study (Fig. 2): (a) agricultural, (b) domestic, (c) industrial, and (d) hydropower.

(a) Agricultural water use is evaluated starting from a critical review of the existing datasets. In this study, the latest ISTAT (Italy's National Statistics Institute) dataset for the agricultural sector (ISTAT, 2010) is adopted. The dataset contains the extent of cultivated areas on the level of each municipality as well as the amount of water used for agriculture at the municipal level. The agricultural water use is modelled assuming an irrigation efficiency of 70% and an irrigation schedule in accordance with the local management practices (Giannini and Bagnoni, 2000). The uncertainty behind this fundamental data set is discussed in chapter 4.

(b) Domestic water use is estimated on the base of population (ISTAT, 2016), considering a daily water need of 150 liters/capita/day, according to the Arno RBA (Autorità di Bacino del Fiume Arno, 2010)

(c) Industrial water use analysis is based on statistics published by the Regional Hydrological Service (Tuscany Region Meteorological Database, 2017). In this study, the focus is on surface water use so, only the withdrawal from rivers or riverbed wells are considered.

(d) Hydropower water consumption is estimated only as water consumption by calculating the water footprint (Mekonnen and Hoekstra, 2012) due to the evaporation from the hydropower reservoir of La Penna. The average annual evaporation is calculated using the empirical formula elaborated by Dragoni and Valigi (1994) with a coefficient representative for Central Italy.

For domestic and industrial water use the percentage of water consumption is assumed as 10% and 5% respectively according to Vahnam and Bidoglio (2013). For agricultural water use, the consumption is assumed at 80%, according to the Italian regulation reference values (MIPAAF, 2015)

The four sectors' water use information, originally at the municipality scale, are converted to the subbasin scale by using a geographic information system to have a common spatial reference with the model.

(iv) Environmental flows

The Environmental Flow (EF) requirements analysis is included to account for the ecological function of the river when analyzing the sustainability of water use in the basin. The EF calculation is derived from the estimation made by Arno RBA (Autorità di Bacino del Fiume Arno, 2016), based on the Low Streamflow method (Reilly and Kroll, 2013), and the regional analysis of low flow in Tuscany provided by Rossi and Caporali (2010). The Q(7,2), i.e. the 2-years return period of the 7-day minimum discharge, is defined as the low flow reference that can be used as hydrologically-based indicator for the minimum EF requirement (Smakhtin, 2001). The Q(7,2)-value for each reach is estimated on the basis of a regionalization approach that identifies hydrologically homogeneous areas and derive the flow duration curves through geostatistical interpolation (Rossi and Caporali, 2010).

(v) Hotspot analysis and trade-off analysis

A hotspot can be generally defined as an area characterized by a high level of a specific indicator. Dealing with WES, the hotspot analysis can be approached from two different perspectives: on one hand, it is possible to identify hydrological hotspots that refer to the level of stress on water resources in a basin and can be measured through a large range of indicators (Brown and Matlock, 2011), such as water scarcity or water vulnerability indicators. On the other hand, it is possible to identify hotspot from an ES perspective as the areas that have the highest demand or supply of ES in the basin (Egoh et al., 2008).

Here, the hydrological hotspots are analyzed using a blue water scarcity indicator defined as:

$$Blue\ Water\ Scarcity_{(x,t)} = \frac{Water\ Consumption_{\ (x,t)}}{Surface\ Water\ Availability_{(x,t)}}$$

where *Water Consumption*$_{(x,t)}$ is the cumulative monthly (t) water consumptive use at subbasin x, and the *Surface Water Availability*$_{(x,t)}$ represents the average streamflow available for withdrawal after subtracting the needed discharge to maintain the environmental flow, on a monthly time step (t) for each subbasin x.

The water consumption is estimated according to the percentages of water consumption defined in the methods (section iii). The average monthly streamflow is an output of the SWAT hydrological model and it represents the net flow at the subbasin scale (i.e. the water available after the upstream withdrawals and losses).

Therefore, an additional indicator of water vulnerability is introduced, to analyze the criticalities deriving from non-consumptive water use before returning to the environment:

$$Blue\ Water\ Vulnerabilty_{(x,t)} = \frac{Water\ Use_{(x,t)}}{Surface\ Water\ Availability_{(x,t)}}$$

where *Water Use*$_{(x,t)}$ is the cumulative monthly (t) withdrawal at subbasin x, and the *Surface Water Availability*$_{(x,t)}$ represents the average streamflow available for withdrawal previously defined.

According to the well accepted definition of Schroter and Remme (2015), ES hotspots are areas which provide large proportions of a particular service (Egoh et al., 2008). Starting from SWAT output, it is possible to identify areas with a high biophysical value of the provisioning and regulating WES (e.g., water supply, sediment regulation, or flow regulation). Regarding water supply, the ratio between the water use (WES demand) and the water yield (i.e. WES capacity to provide surface water) is analyzed in every subbasin:

$$WES\ provisioning\ hotspots_{\ (x,t)} = \frac{Water\ Use_{\ (x,t)}}{Water\ Yield_{(x,t)}}$$

where *Water Use*$_{(x,t)}$ is the cumulative monthly (t) withdrawal at subbasin x, and *Water Yield*$_{(x,t)}$ is a SWAT output that represents the contribution of every subbasin x to the total streamflow. It is calculated as the monthly (t) net average amount of water that is locally converted to streamflow, independently from the water coming from upstream. Values exceeding 1 indicate that the subbasin is demanding more services than locally produced, while values between 0 and 1 indicate WES supply hotspots, i.e. areas that produce services that can be used in other subbasins.

For sediment regulation, the model directly provides the value of sediment yield (tons/ha) that represents the transported sediments in each reach; the inverse of sediment yield Is used to map the efficiency of sediment regulation at the subbasin scale. Flow regulation can be evaluated at different levels of details (i.e. HRU or subbasin), considering a runoff index that is the ratio between surface runoff and precipitation.

Integrating the results obtained for single WES indicators allows for evaluating trade-offs and synergies between different WES in the basin. Trade-offs occur when the presence of one service excludes the presence of another service or the services are negatively correlated, while synergies arise when or multiple services can coexist in the same area, having a positive correlation (Rodriguez et al, 2006). Here, the focus is on local trade-offs and synergies, comparing the level of different WES in each subbasin to identify existing relationships between services. This can give additional insights into the hydrological behavior of the basin and help decision makers understanding the hidden interconnections between different WES.

2.3. Results

Following the methodology described above, the first step is the identification of the WES to be analyzed (section 2.3.i). Section 2.3.ii contains the calibration and validation results of the SWAT Model as well as the annual average hydrological balance, determining the green/blue water partitioning. Then WES hotspots and trade-offs between different WES on a monthly basis are analyzed (section 2.3.iii and 2.3.iv).

(i) WES identification

Based on the water management plan of the Appenino Centrale District, the preliminary analysis provides an insight into the interconnected demands and risks associated with water by identifying the major challenges and the key WES in Casentino, Val di Chiana and Valdarno Superiore areas. In the northern sub-catchment (Casentino), the main land use determines a less anthropogenically affected environment. Nevertheless, industry, together with agriculture and domestic water use, is causing pressures on water resources. Concerns derive also from erosion connected with flow regulation. In fact, the decrease in forest maintenance and land use change in the valley has caused a gradual increase of the hydrogeological risk in the area. The southern part of the catchment, Val di Chiana, is mainly dedicated to agriculture. Val di Chiana is among the three main irrigated districts in Tuscany; with both irrigated crops and rainfed agriculture. According to the existing plan, also this sub-catchment is suffering erosion problems. The downstream part of the case study area, Valdarno Superiore, is characterized by the presence of a medium size hydropower plant, with a reservoir that can also be used for flow regulation and that is affected by sedimentation. Water use in the area is mainly urban. All the challenges previously identified are then associated to the related ecosystem services that need to be quantified. Based on the proposed assessment, the analysis focuses on water supply for the different sectors that represent the main provisioning WES and erosion and flow regulation as regulating WES (Tab 2).

Tab. 2.2 Water-related ecosystem services (WES) assessment of demands. The WES demands and the associated thresholds (low, medium, high) are determined from the analysis of the existing Arno RBA management plan results (qualitative analysis and indicators shown in the methodology section) for three main sub-catchments.

	WES demand				
	provisioning WES				regulating WES
Sub-catchments	**Irrigated agriculture**	**Industry**	**Urban**	**Energy**	**Sediment/Flow regulation**
Casentino	*medium*	*medium*	*medium*	*n.a.*	*medium/high*
Valdarno Superiore	*low*	*low*	*medium*	*medium/high*	*medium*
Val di Chiana	*high*	*medium*	*medium*	*n.a.*	*medium*

(ii) Ecohydrological modelling

Calibration and validation

The selected WES are linked to specific ecohydrological processes from which they derive and evaluated by analyzing specific output variables of the SWAT model (fig. 2.3)

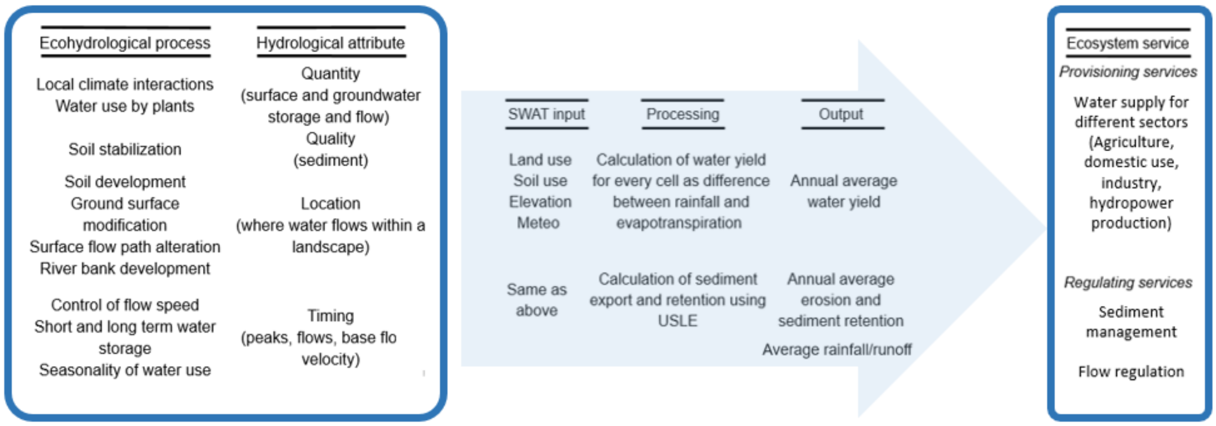

Fig. 2.3 Modelling framework. The scheme shows the link between hydrological processes and the related ecosystem services that can be quantified through a hydrological model. The arrow synthetizes the SWAT model input/outputs

The SWAT parameters were calibrated separately in the three main sub-catchments to better differentiate their hydrological characteristics.

The calibration was based on the monthly average runoff outputs at three gauges representative of the three main sub-catchments and it has focused on the parameters influencing the peaks and base flow behavior. After a sensitivity analysis on the parameters that influence surface hydrology, a set of six parameters have been chosen for the calibration, using the SUFI-2 algorithm (Abbaspour, 2007). The final set of parameters for each sub-catchments is shown in table 2.3.

Tab. 2.4 Calibration parameters set for the three main sub-catchments (GW_DELAY=groundwater delay (days); ALPHA_BF= baseflow factor (days); GWQMN=threshold for return flow (mm H_2O),GWREVAP=groundwater revap factor (dimensionless), REVAPMIN= shallow aquifer threshold for revap (mm H_2O), RCHRG= percolation factor (dimensionless)

	GW_DELAY	ALPHA_BF	GWQMN	GWREVAP	REVAPMIN	RCHRG
Casentino	127	0.048	4200	0.12	270	0.1
Valdarno	85	0.2	4000	0.1	300	0.1
Val di Chiana	13	0.048	4000	0.1	356	0.3

According to Moriasi et al. (2007), statistics show consistent results with respect to discharge (i.e. $R^2 > 0.5$, NSE > 0.5, RSR < 0.7 and -25 < PBIAS < 25). The model, while yielding performance statistics always within acceptable ranges, underlines a different behavior in the two main sub-catchments: Casentino and Valdarno areas show an underestimation of the runoff in calibration especially for peaks; on the other hand, Val di Chiana shows a general overestimation of discharges (Fig. 2.4.).

Tab. 2.3 Calibration and validation statistics divided for the three main sub-catchments.

	R^2		**NSE**		**RSR**		**PBIAS**	
Sub-catchments	*Cal*	*Val*	*Cal*	*Val*	*Cal*	*Val*	*Cal*	*Val*
Casentino	0.87	0.75	0.79	0.89	0.44	0.49	17	-1.3
Valdarno Superiore	0.71	0.51	0.69	0.77	0.56	0.79	14.8	-2.3
Val di Chiana	0.82	0.75	0.79	0.88	0.45	0.54	-14.7	0.36

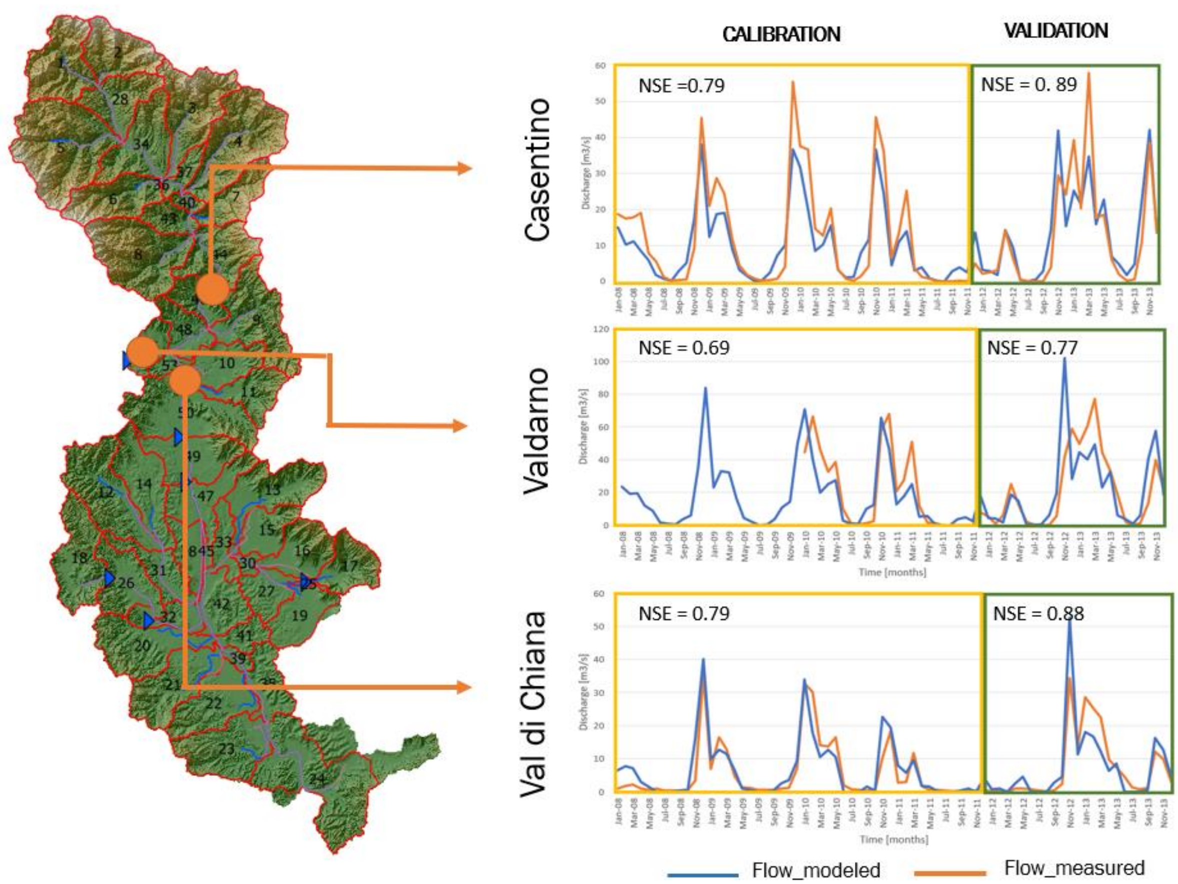

Fig. 2.4Calibration and validation runoff time series comparison

aAnnual water balance provisioning and regulating ES

The long period water balance calculated with SWAT gives significant insights into how climate conditions, land use and soil, influence the hydrological behavior of the basin and determine the blue/green water partitioning. The percentages of streamflow and evapotranspiration over precipitation, calculated with the model calibrated at the previous step as annual average, are respectively 25% and 46% . These values are in line with other studies with similar climate and can be considered representative of the area (Glavan and Pintar, 2012).

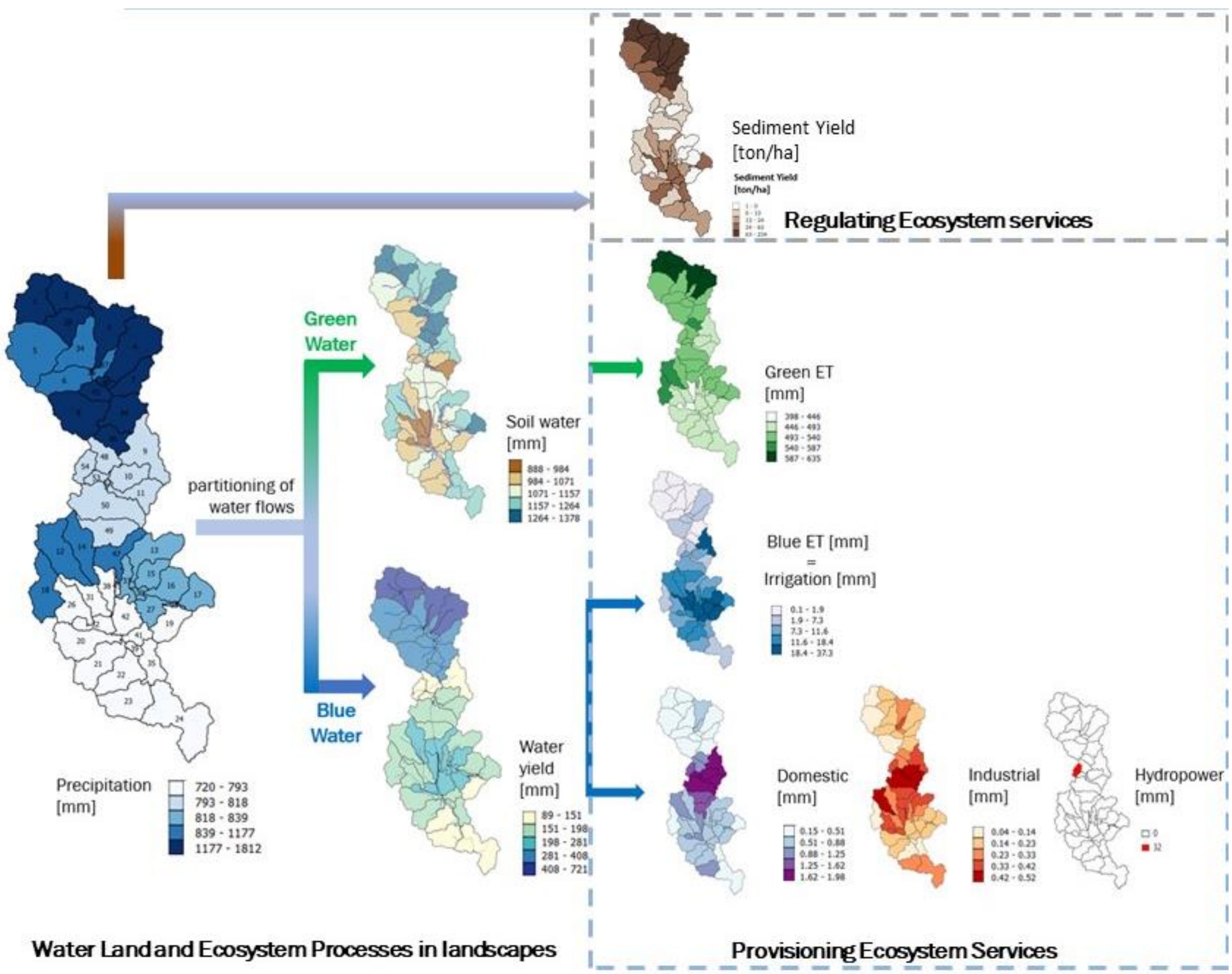

Fig. 2.5 Water balance overview. The left part of the scheme shows the effects of the interaction between water and land on the partitioning of precipitation into green and blue water flows and the potential provisioning water-related ecosystem services. In the right part of the scheme the two boxes identify the actual provisioning and regulating services, as annual averages.

In absolute terms (Fig. 2.5.), the basin receives an annual average precipitation of 2282 hm^3, of which 576 hm^3 turns into surface blue water and 1056 hm^3 into green water. The actual evapotranspiration ET, calculated with Hargreaves and Samani equations, exhibits annual average values between 413 and 617 mm with higher values in the Casentino area, in accordance with other studies (e.g. Brugioni et al., 2010). The total evapotranspiration can be divided into green and blue ET to differentiate the water coming from irrigation. Analyzing the irrigated agriculture areas, the annual average ET is around 33.1 hm^3 of which 17.8 hm^3 are blue ET (equal to the 56% of the total ET); this represents the demand of green and blue provisioning WES for the agricultural sector.
Results indicate that the highest amount of water yield (i.e. the net amount of water that contributes to streamflow and that represents the potential capacity of the basin to provide WES) originates in the northern part of the basin characterized by forest areas. In contrast, the southern part of the basin, which is mainly dedicated to agriculture, gives a minor contribution to the overall water yield.

The water provisioning for the different sectorial uses, which represent the actual demand of the provisioning WES, is estimated for every sector at the subbasin scale. Besides the already mentioned agricultural sector, that is the most water intensive sector (48% of the total water use), domestic and industrial water use represent the 30 % and 21% of the total respectively. Regarding the hydropower water consumption, the estimated evaporation from La Penna reservoir, located at the closing section of the basin, is 986 mm/year. Considering that the lake has an extension of 72 hectares, a total of 709,800 m^3 evaporated every year representing the water consumption for the hydropower sector that accounts for the 1% of the total water use (Tab. 2.5).

Tab. 2.4 Water use for the different sectors in the three main sub-catchments.

	Domestic [hm^3]	**Agricultural [hm^3]**	**Industrial [hm^3]**	**Hydropower [hm^3]**	% total use
Casentino	3.19	4.28	2.93	0	20
Valdarno Superiore	5.71	2.51	2.99	0.71	23
Val di Chiana	6.62	18.65	4.94	0	57
% total use	30	48	21	1	

.

(iii) Evaluation of hotspots and ES fluxes.

The annual water balance itself does not provide a comprehensive picture of the hydrological processes, because it does not represent the seasonal variability which is fundamental for highlighting potential hotspots in the basin. Starting from the hydrological hotspots, the blue water vulnerability and scarcity assessment shows that, whereas the northern part of the basin does not suffer either of blue water scarcity nor of vulnerability throughout the entire year, the southern part exhibits several hotspots in summer - mainly due to the high agricultural consumption. The vulnerability analysis allows also identifying territories that - even if not associated with periods of water scarcity - might be vulnerable to water stress due to the summer withdrawals (cf. the area in the central part of the basin in Fig. 2.6).

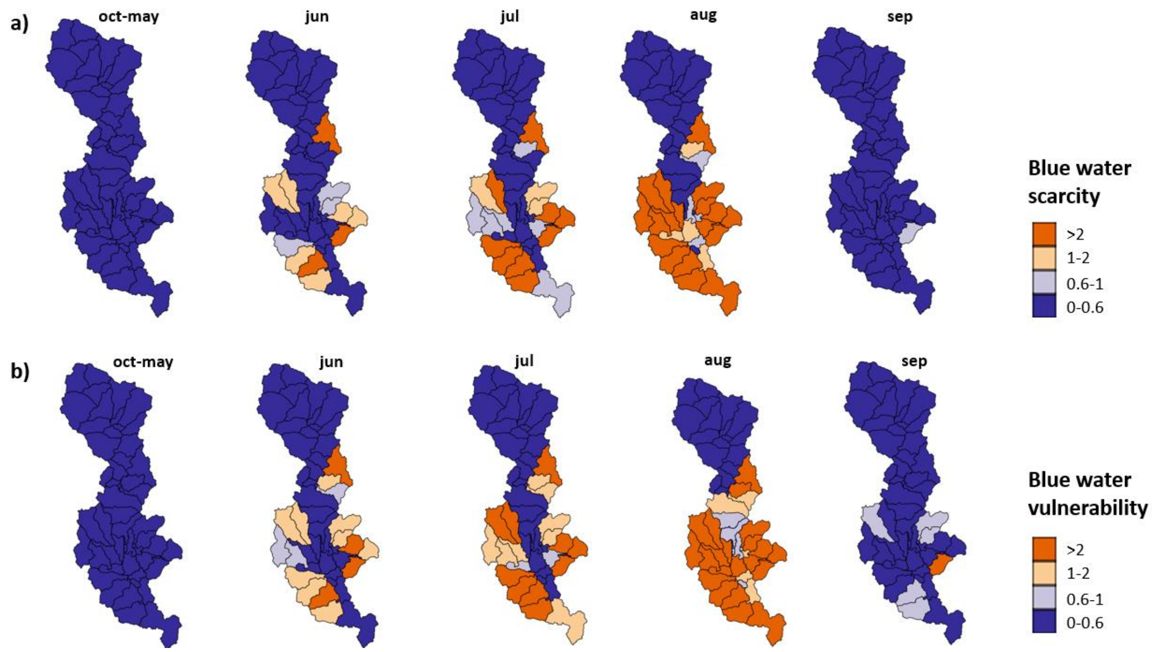

Fig. 2.6 Monthly assessment of (a) blue water scarcity, and (b) blue water vulnerability assessment.

The analysis of WES provisioning hotspots shows the local contribution to the production of provisioning WES at the subbasin scale. The supply hotspots (areas with a ratio between water use and water yield < 1) are mainly located in the northern part of the basin and in sparse subbasins located in the southern part of the catchment. This result emphasizes the hydrologic dependency of the central part of the basin (Valdarno) to the northern supply hotspot (Casentino). In Val di Chiana, it is possible to identify WES fluxes that link the few supply subbasins with the rest of the territory, where the provisioning WES demand is mainly located (cf. Fig. 2.7). The results for the month of August highlight the critical situation due to agricultural withdrawals already identified by the hydrologic hotspots analysis.

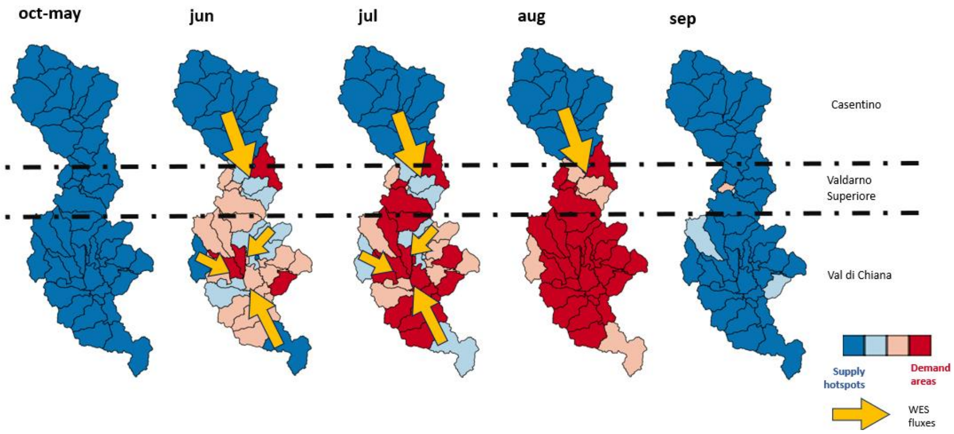

Fig. 2.7 Monthly ES hotspot evolution and qualitative assessment of WES fluxes. The arrows represent the connections between WES supply hotspots and WES demanding area in a qualitative way.

The sediment yield maps identify hotspots in the river basin, confirming the issues related to erosion in both Casentino and Val di Chiana sub-catchments. These results, although not calibrated over time due to the absence of data, show accordance with sedimentation volumes estimated in the reservoir located at the closing section (Rossi, 2007). The analysis of flow regulation shows a less defined distribution pattern, but it is possible to identify lower levels of flow regulation (i.e. higher level of the low index) especially in some subbasin of the eastern part of Casentino and in the central part of Val di Chiana, where the combination of soil type and agricultural land use is responsible for higher runoff levels (Fig. 2.8).

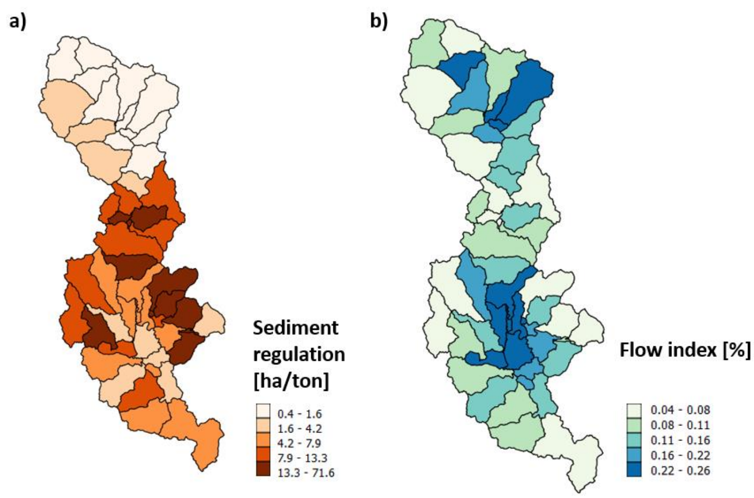

Fig. 2.8 Sediment and Flow Regulation maps. Figure a) shows that the higher level of sediment yield are associated with the north eastern part of the basin, especially due high level of rainfall. Figure b) shows that the higher level of flow index in the central part of Val di Chiana, due to its combination of soil type and land use.

(i.v) Identification and evaluation and of WES co-occurrences: trade-offs and synergies.

For every subbasin, the correlation between the different WES is analyzed (Fig. 2.9). By combining the potential capacities to provide selected WES (i.e. water yield, sediment regulation and flow regulation), it is possible to investigate local synergies and trade-offs. Results show a consistent behavior in the three main sub-catchments where every couple of WES analyzed, if correlated, have similar trends.
Sediment and flow regulation exhibit synergistic relationships for subbasins in Valdarno and Casentino reflecting the correlation between runoff and soil erosion in the river basin. No relationship was identified in Val di Chiana suggesting that soil erosion in this area is mainly determined by soil characteristics instead of the runoff effects.
In contrast, water yield and flow regulation show an inverse relationship highlighting the trade-offs between the increase of streamflow availability and the possibility of regulating flow, especially in Val di Chiana and Valdarno. In Casentino the trade-off is not recognizable, and this can be due to the predominance of lateral flow in the contribution to its water yield.
For Casentino and Valdarno Superiore, a clear trade-off between sediment regulation and water yield is identified, while no relationship was recognized in Val di Chiana suggesting that already mentioned prevalence of soil characteristics on the sediment regulation of the area (Fig. 2.9).

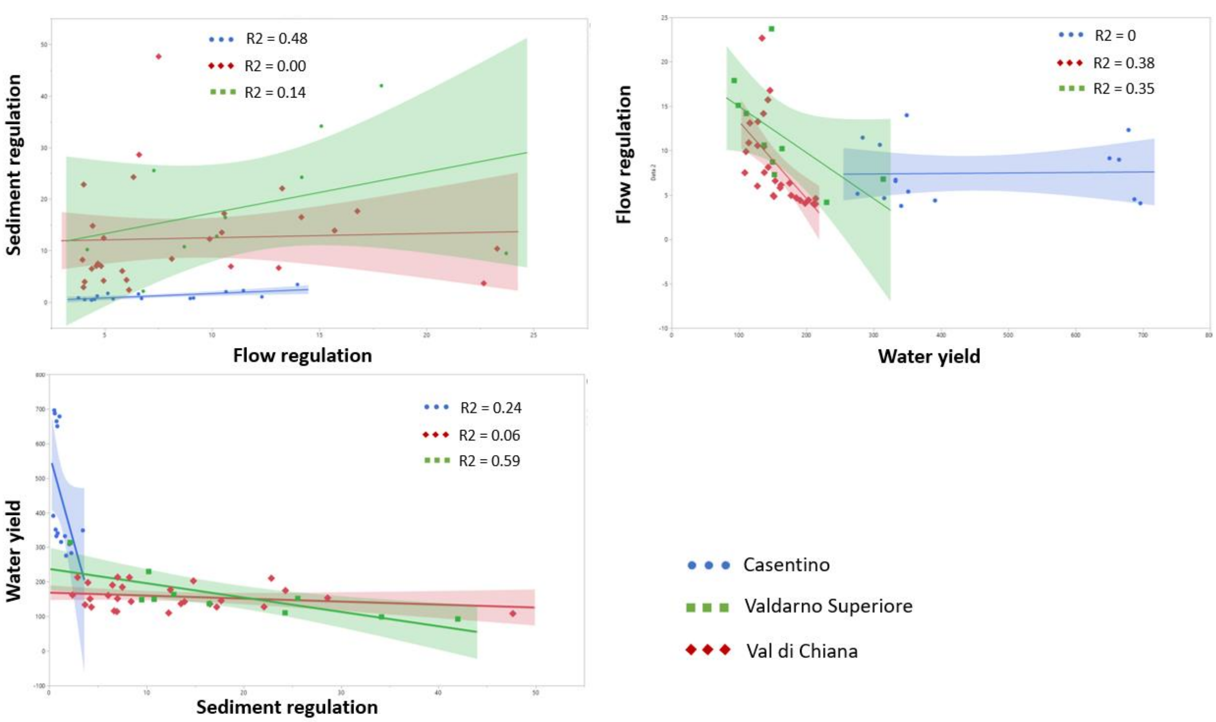

Fig. 2.9 Trade-off and synergies analysis: Each graph represents the analysis of the potential correlation between different water-related ecosystem services in the three main sub-catchments (Casentino, Valdarno Superiore and Val di Chiana). Each point represents a subbasin and its color represents the sub-catchment grouping. The linear regression line with 95% confidence intervals and the variance R^2 are shown for each sub-catchment group.

2.4. Discussion

The developed framework provides a spatiotemporal assessment of WES that highlights the human-environment relationships in the Arno river basin and suggests a novel approach to set up management strategies that can support human well-being while simultaneously preserving ecosystem functions.

Overall, this case study provides significant insights into the hydrological behavior of the basin on a monthly time step and useful information regarding the availability and use of water resources in the basin. The water balance identified the differences of water yield between the northern and the southern part of the basin, according to the distribution of the meteorological variables (mainly the precipitation) and the combined effect of the land use and soil. The land use strongly influences also the green/blue water partition as shown by the prevalence of green water flows in the northern part of the basin where forest is mainly located. The analysis regarding the water use shows a pronounced difference between the three main sub-catchments: the agriculture is predominant in the southern part of the basin, while industrial water use appears more scattered and concentrated around industrial districts. The domestic water use, being calculated as a function of the number of inhabitants, reflects the population density of the municipalities.

Water scarcity and vulnerability indicators identify the main issues regarding water and quantify the level of stress that users put on water resources. This allows us to map the hydrologic hotspots in the Val di Chiana and stress the importance of adopting solutions to control water use in agriculture and increase of irrigation efficiency (Fig. 2.6). On the other hand, an ecosystem-based approach, as the analysis of WES provisioning hotspots, highlights another fundamental aspect that is the flow of WES from the supply hotspots to the main demanding areas. Identifying the WES dependency (i.e. the connection between WES supply/demand areas) among different territories provides fundamental information to help supporting water stewardship strategies in the basin as, for instance, payment for ES intervention (cf. Gómez-Baggethun et al., 2010). Thus, water-provisioning issues can be approached both from a local perspective (e.g. reducing water use/increasing water use efficiency) and from a broader scale where the territories that produce WES are protected to improve their provision capacity downstream.

Regarding sediment regulation, main contributing areas are identified. In Casentino, erosion is affected by the morphology of the area, the rainfall pattern and the geology characterized by sequences of marl and sandstone with different resistances to erosion, which causes the development of gullies (Cavagna and Cian, 2003). In contrast, land use change is the main cause of erosion in Val di Chiana, where the enlargement of agricultural areas has reduced its sediment retention capacity. This information is crucial to identify focus locations for specific interventions to reduce sediment production (e.g. by forest management, river structures and specific agricultural practices). Flow regulation is less defined in its distribution because multiple drivers influence it, such as rainfall distribution, soil and land use.

The analysis of single hydrological and WES hotspots does not provide the comprehensive view needed to deal with the complex nexus of processes typically involved in the water system. Many communal factors (i.e. the hydrological behavior, the effect of water use and all the complex relationships in between) influence the level of WES production in a territory. This underlines the importance of evaluating the extent to which trade-offs and synergies might arise between different potential services. The analysis of the existing correlations among water yield, sediment regulation and flow regulation show that each subbasin is characterized by a proper combination of WES production capacity and that is possible to identify specific correlations among WES in subbasins of the same area (i.e. Casentino, Valdarno Superiore and Val di Chiana). This suggest that water management should focus on the multiple effect that decisions can have in each specific landscape and set up policies that consider, from an ecosystem-based perspective, the heterogeneous responses of the territory to certain type of measures. In Valdarno and Val di Chiana, for example, increasing water yield is associated with the decreasing of flow regulation. Any intervention to increase water yield could cause important counter effect, therefore only a detailed analysis on the feedbacks of different WES could drive an informed decision-making that can enhance the overall capacity of WES provision of the area.

3

Ecosystem services-based scenario analysis in the Arno river basin

3.1. WES as a support for decision making

The assessment of WES in Chapter 2 provides a useful overview of how water interacting with terrestrial ecosystem contributes to human wellbeing, identifying the areas that are crucial for WES production (i.e. hotspots) and the relationships between different ecosystem services. Moreover, Chapter 2 highlights how the analysis of co-occurrences and feedbacks between different WES should drive an informed decision-making that can enhance the overall capacity of WES provision of the area.

A landscape is not a static entity but is undergoing continuous changes driven by several drivers. Any change in a watershed could lead to multiple effects in term of WES production. Human decisions and actions largely represent the main responsible for environmental change and thus for the change of the ecosystem services produced. Therefore, evaluating the effects of different management strategies from an ecosystem service perspective is fundamental.

Taking advantage of the model described in Chapter 3, the upstream part of the Arno river basin is analyzed in terms of its responses to different management scenarios. Firstly, the effects of land use change are considered, investigating how the implications contained in European agriculture policies might affect the WES production. The Common Agricultural Policy (CAP) is the reference for the agricultural sector in Europe. It contains guidelines for the farmers, aiming at the implementation of agricultural practices that are expected to have positive effect on the environment (Van Zanten et al., 2014). Every change in agriculture is going to affect the state of land water resources, whose nexus has been already identified in Chapter 2. Based on the guidelines of CAP for the period 2014-2020 (European Commission, 2014) that are pushing for the development of greener agricultural practices, I analyzed the effects of different kinds of voluntary measures on the WES production in the watershed.

Subsequently, I analyze a scenario dealing with increasing water use. Due the importance of the agricultural sector in the economy of the area, it is fundamental to evaluate the effects that expanding this economic sector might have on the overall watershed equilibrium.

3.2. Methods

Scenarios analysis is implemented by comparing the SWAT output based on the original land use (LU) dataset (i.e. the existing land use as defined in Chapter 2) with SWAT output derived from the model modified according to each scenario (i.e. modifying the LU map or the water abstraction in SWAT). For each scenario, the effects are assessed in terms of the change of the main hydrological variables as well as by analyzing indicators of WES hotspots.
For sediment regulation the value of sediment yield (tons/ha) is evaluated while flow regulation is estimated with the runoff index that is the ratio between surface runoff and precipitation. In addition, a percolation index (defined as the ratio between percolation and runoff) is introduced and quantified. The water yield is assumed as a proxy variable for blue water provisioning services.

Starting from the baseline simulation, four scenarios have been evaluated:

- Scenario 1: afforestation of marginal lands
- Scenario 2: implementation of soil conservation measures (e.g. contour ridges)
- Scenario 3: increasing the agricultural sector areas (land use change)
- Scenario 4: increasing water use in the agricultural areas.

LU change has been implemented in SWAT taking advantage of the land use update (Lup) routine of the model that allows HRU fraction updating during a simulation run. The update consists in the identification of the land use classes to be changed and the definition of their new LU composition. The LU change can be realized at the subbasin scale, therefore allowing a spatial differentiation of the interventions, according to their suitability in the different areas.

For every HRU of the subbasins affected by the LU change, the model defines the new LU partitioning. It is also possible to set up multiple land use change at a time or to define different periods of updates for each land use class.

3.3. Results

Evaluating the effect of afforestation

The effect of afforestation of marginal lands is the first scenario examined. This kind of intervention has been modelled in SWAT assuming that parts of the marginal lands are converted into forest for the entire simulation period. The identification of the areas suitable for this kind of intervention has been realized using a geographic information system. All the areas that are classified as marginal lands (i.e. shrubland or unused agricultural areas) that are connected to forested areas are assumed as suitable for afforestation and converted to forest for the 50% of their extension (Fig. 3.1)

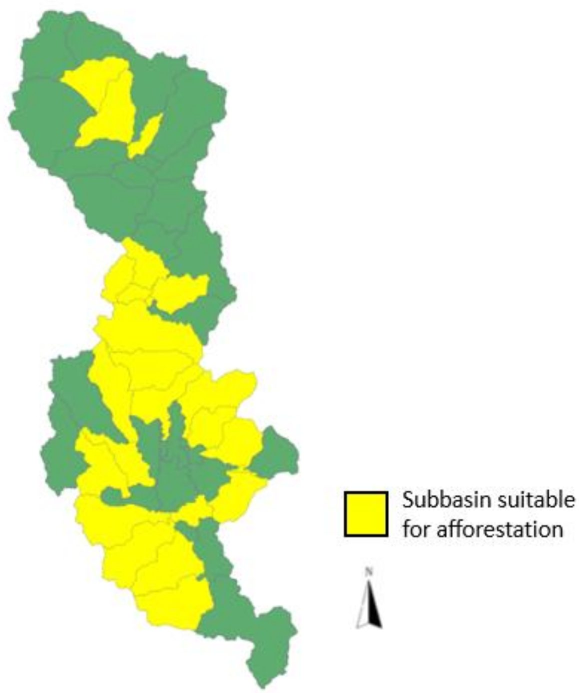

Fig. 3.1 Distribution of the areas that are suitable for afforestation intervention. The map shows the subbasin of the SWAT model where minimum of 20% of the areas are identified according to the selection criteria for afforestation. The potential area for this kind of intervention is around 200 km^2.

The annual water balance (Tab. 3.1) of the entire catchment exhibits some tendencies: results show that this scenario of intervention mainly affects the sediment yield, determining a mean reduction of around 4.5%. The slight increase in evapotranspiration is almost negligible suggesting that the influence of the selected land use change scenario is not causing big differences in the green water balance. It is interesting to highlight the effect of afforestation on local surface water availability showing a decrease both in terms of water yield and surface runoff.

Tab. 3.1 Quantitative evaluation of the afforestation scenario calculated as the difference with baseline scenario (annual averages for the entire basin and for selected subbasins identified as suitable for afforestation)

Average changes [%]	**Evapotrans-piration**	**Soil Water**	**Surface runoff**	**Percolation**	**Water Yield**	**Sediment Yield**
for entire basin	0.27	-0.31	-1.67	0.42	-0.81	-4.50
for sel. subbasins	0.54	-0.62	-3.36	0.93	-1.87	-8.94

If we look at the localized effect of afforestation in the subbasins that were identified as suitable for this intervention, we see a stronger response. In fact, the behavior already depicted by the results of the entire catchment is almost doubled, highlighting the tradeoff between the effect on sediment regulation and the availability of local water resources. Afforestation shifts water flow inducing an increase of percolation together with a decrease of runoff. This means a positive effect in terms of flow regulation, but it might also cause a decrease in surface water availability. As already shown in Chapter 2, there is a clear tradeoff between sediment regulation and water yield, therefore it is fundamental to properly identify the multiple effects of afforestation on these two ecosystem services.

Effects of conservation practices: contour ridges

Contours ridges are constructed along the contour line, usually spaced between 5 m and 20 m. The first 1-2 m above the ridge is usually used for cultivation, whereas the remaining serves as a catchment. The height of each ridge varies according to the slope's gradient and to the expected depth of the runoff water retained behind it. They may be constructed on wide range of slopes, from 1% to 50%. Building these ridges along contour lines of hilly areas is a common conservation measure, especially in arid or semi-arid areas, for reducing runoff and its erosive potential (Abouabdillah et al., 2017). This kind of measure can be very effective in barren areas prone to erosion; it also can implement water harvesting. Here, the use of contour ridges has been considered as a measure to reduce sediment transport in the catchment. It has been applied to olives orchards, one of the most traditional and diffuse type of cultivation in the hilly areas of Tuscany.
The analysis of contour ridge effects has been carried out only considering the reduction of soil losses associated to the intervention, affecting the USLE conservation practice factor (P_{USLE}). This parameter describes the level of intervention in the catchment compared to the baseline scenario. According to existing literature (Khelifa et al., 2017 Salmoral et al. 2017) the value of P_{USLE} for olive fields has been modified and set equal to 0.5 in the areas with slopes between 10% and 20%, while a P_{USLE} of 0.6 has been adopted for slopes higher than 20%.

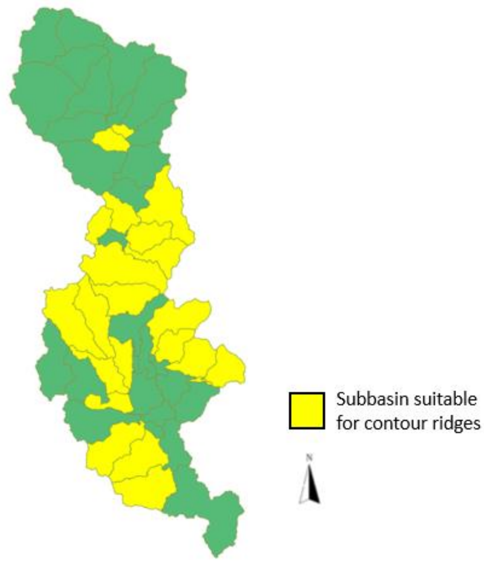

Fig. 3.2 Distribution of the areas that are suitable for the constructing of contour ridges. The map shows the sub-basin of the SWAT model with olive cultivation in slopes higher than 10% (5.7°) corresponding to an area of about 100 km^2.

For the entire catchment, the reduction of sediment yield is around 0.3%. This is due to the limited share of olive cultivation (ca. 5% of the total land use). Thus, the effects of this scenario are very localized and visible at the subbasin scale, where the presence of contour ridges determines an average decrease of sediment yield of around 2.5%.

Intensification of the agricultural sector: extending olive and grape cultivation

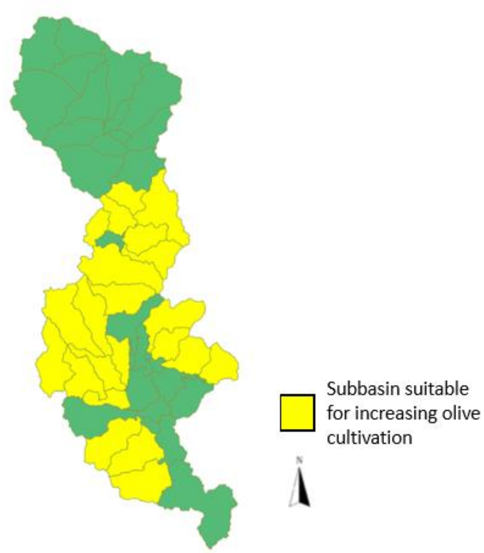

Fig. 3.3 Distribution of the areas suitable for increased cultivation of olives and grapes. The map shows the subbasin of the SWAT model, where forest or marginal land can be converted into olive or grape cultivation (ca. 30 km^2).

This scenario has been analyzed considering an increase of grapes and olives cultivation in the territory, using areas not cultivated at present time. The total area affected by this scenario is about 33 km^2 (equal to 1.5% of the total case study area). In particular, I assumed a new land use for this area made of 50% of grapes and 50% of olives trees.

The results in terms of average annual values show slight effects of the scenario on the main hydrological variables, mainly due to the extension of the area involved. Focusing the analysis on those subbasins affected by the land use change sheds some light on some major effects, especially in terms of surface runoff decrease

Tab. 3.2 Quantitative evaluation of olives and grapes cultivation scenario calculated as the difference with baseline scenario (annual averages for the entire basin and selected subbasins)

Average change [%]	**Evapotranspiration**	**Soil Water**	**Surface runoff**	**Percolation**	**Water Yield**	**Sediment Yield**
for entire basin	-0.03	0.13	-0.19	0.15	-0.12	-0.06
for sel. subbasins	-0.07	0.37	-0.84	0.56	-0.52	-0.55

.

Intensifying agricultural sector: increased water use

In another scenario I evaluated the effect of increasing the water withdrawals associated to the agricultural sector, considering a 20% of added water demand for this sector. Based on a recent total agricultural water use of 25.4 Mm^3, it is assumed an increase of 5.8 Mm^3 for the summer period in those subbasins which are characterized by irrigated agriculture.

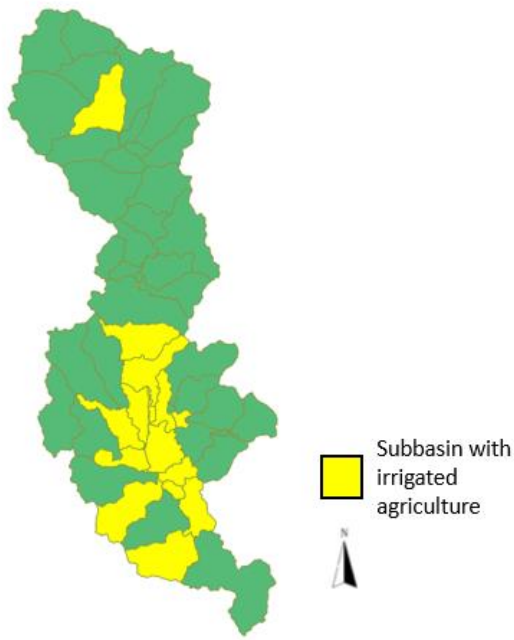

Fig. 3.4 Distribution of the areas characterized by irrigated agriculture. The map shows the prevalence of irrigated agriculture in Val di Chiana area.

This scenario is firstly analyzed in terms of the effects that an intensification of water use in agriculture can have in terms of the overall water availability. The water scarcity and vulnerability indicators are mapped to spatially evaluate the effects of water intensification at the subbasin scale. Compared to the baseline scenario, results show how agricultural intensification determine a worsening of the levels of water scarcity and vulnerability especially in in the central part of Val di Chiana. In the northern part of the catchment also Casentino starts to show an incipient deterioration of its water security (Fig. 3.5).

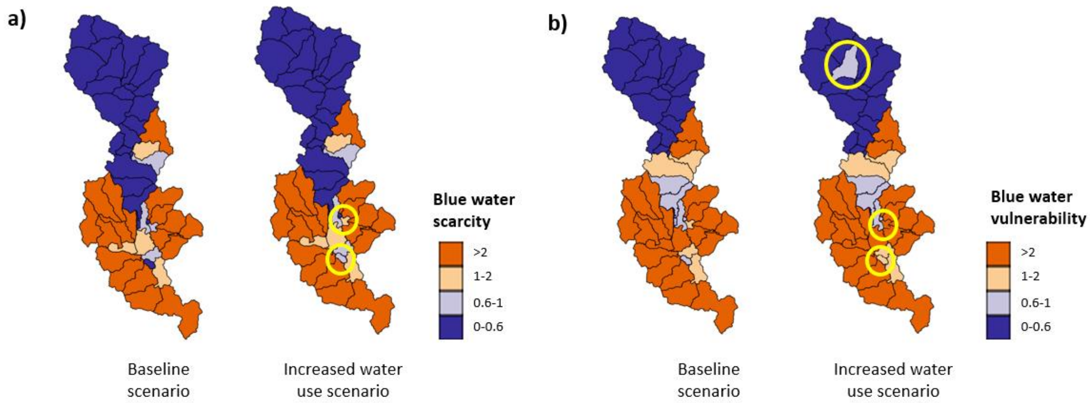

Fig. 3.5 Water scarcity and vulnerability changes under the water intensification scenario. Yellow circles identify the new hotspots induced by the increase of water withdrawals

3.4. Discussion

Water underpins essential ecosystem services that are strongly influenced by watershed management. Understanding the hydrological dynamics associated with the ecological characteristics of the landscape and the dynamic processes associated with land use and land cover changes allowed formulating research hypotheses and consequent results oriented to support watershed management through quantitative evaluation of WES production changes. SWAT modeling has shown how land use changes driven by agricultural policies could cause multiple effects at the watershed scale and the trade-offs that might arise.

The study outcomes should be interpreted as a pilot implementation of WES-driven management at the watershed scale. The WES assessment provides useful information that can be extended to other watershed and support the improvement of the WFD

The scenario analysis could be integrated with other considerations to include other services that might be important. For example, the afforestation intervention besides affecting the regulation of flow or sediment transport and the overall water balance, produce other services, such as wood production or carbon storage that are not taken into account but that might be an important factor to be considered for a more comprehensive analysis.

4

The small-scale water-food nexus: Water Footprint analysis as a tool to enhance water use and support water management

4.1. The importance of analyzing water use

In the first chapter, I identified the role of society as an element that produces transformation to the system and reacts with adaptation to its evolution as a principal driver of change of the water-land system. It's therefore crucial to carefully evaluate the human-induced modification to the system in order to manage and possibly reduce the associated impacts on ecosystem health. Water withdrawals for the different sectors represent often the main concern in watershed management, determining situations of scarcity where there is a mismatch between demand and ecosystem capacity. Progressively shifting from a focus on building supply infrastructure to satisfy the demand, water managers have recognized the importance of improving their understanding on how water is used to decrease pressures on increasingly scarce water resources (Gleick, 2003). Chapter 2 highlighted the importance of quantifying the water use to support a sound watershed management and showed the difficulties in collecting consistent and reliable data on withdrawals. Despite the importance of the problem there is still little organization in the methods to estimate or collect the data regarding water use (Morrison et al., 2010).

Water Footprint (WF) methodology represents an opportunity to provide an operative answer to the necessity of precisely quantifying the water use as a support of sound watershed management. WF is a multidimensional indicator of water use that needs to be defined in time and space, allowing the evaluation of the impacts of human activities in terms of water use and impacts on the hydrosphere.

In its first formulation - defined in the Water Footprint Assessment methodology (WFA, Hoekstra and Chapagain, 2007) - WF includes three components: green water, i.e. the rainwater stored in the soil available to plants; blue water representing surface or ground water volumes; and gray water, which represents the water polluted during a production process. Overall, the purpose of WF is to investigate the link between the direct and indirect consumption of water and the impacts on the local water system, allowing to identify the main problems and, therefore, to develop an efficient resource management (Hoekstra et al 2011). WFA can support watershed management in multiple ways: defining a benchmark for setting up water saving strategies or revealing hidden costs and impacts of production of goods and services (Hoekstra and Chapagain, 2007), triggering compensation measures of unbalanced water consumption (Ravi Shankar and Jayasri, 2015), as well as sensitizing and contributing to a better transparency to consumers (Alessi and Bologna, 2015).

The rationale behind the WFA assessment is to determine the impacts associated to the entire life cycle of human activities. In fact, the WFA has a structure similar to Life Cycle Assessment (LCA, as defined in ISO 14044, 2006), being divided into goal and scope definition, accounting and impact assessment (Fig. 4.1).

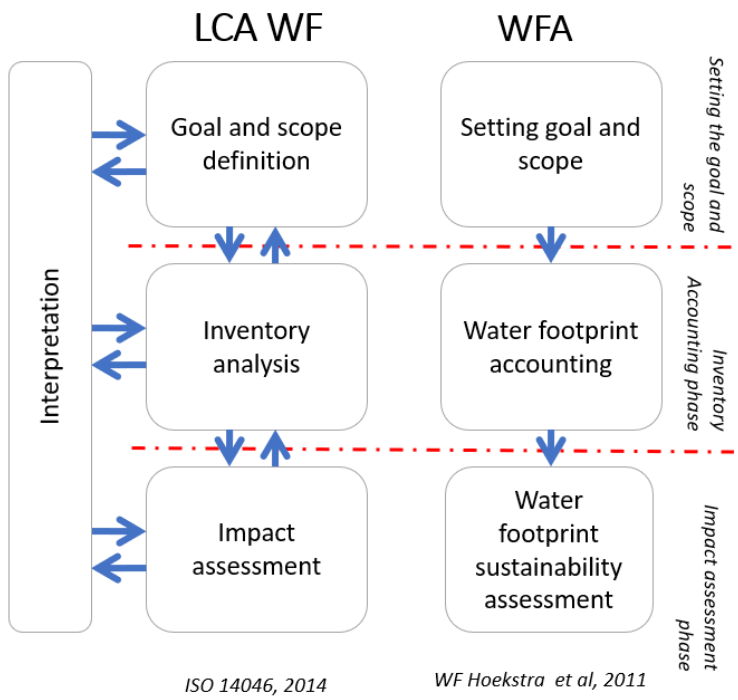

Fig. 4.1 Comparison of water footprinting structure in LCA and WFA assessment

Since the first release of the WFA methodology, many studies stressed the importance of integrating LCA and WFA approaches (Berger & Finkbeiner, 2010, Jefferies et al., 2012). In fact, a comprehensive assessment of resource use within the life cycle cannot be complete without taking into account water. Therefore, the WFA can be considered an important improvement to the classical LCA methodology. On the other hand, the WFA can take advantage of the LCA, because it provides other environmental indicators that can promote an understanding of the real impacts of the analysed system (Boulay et al., 2013).

Despite their multiple similarities, the two theories developed independently. Within the LCA community, a different WF methodology has been progressively elaborated. This method was formalized in 2014 as an ISO standard (ISO 14046, 2014) that defines WF as a component of LCA methodology (ISO 14044). The evolution of WF has been characterized by an increasing contrast between the LCA and WFA communities (Hoekstra et al., 2009; Pfister et al., 2009; Hoekstra 2016; Pfister et al. 2017). The main difference between the two approaches belongs to the impact assessment phase. The WFA community supports the idea of WF as a quantitative assessment (i.e. volumetric) of freshwater appropriation that can support a better understanding of the hotspot at a watershed scale. In contrast, the LCA community, promotes the idea of WF as a sustainability indicator that - after being weighted based on the local water stress - can be used to assess and compare the sustainability of production chains.

A case study has been developed to compare these two approaches, highlighting their differences and potential synergies to support a better understanding of water use and support water management decision making.

4.2. Materials and methods

Food production is the sector with the most relevant impact on fresh water consumption (FAO, 1996), as also highlighted in chapter 2 by the analysis of water demands in the Arno river basin. It is therefore strategic to start from this sector to investigate the impacts of goods production on water resources. Since data availability on water use in agriculture is scarce and fragmentary, this case study provides also the opportunity to clarify the actual impacts of this sector on water resources, setting a benchmark for future evaluation.

As a pilot case study, I analysed WF of wine production. The production of wine stands out as one of the most relevant productions for sustainability assessment, due to its economic relevance and distribution on world markets (Bonamente et al., 2016). Multiple methodologies were applied to evaluate WF of wine production considering freshwater consumption and impacts on freshwater resources (Herath et al., 2013; Lamastra et al., 2014; Quinteiro et al., 2014; Bonamente et al., 2016). This analysis aims at comparing the two WF methodologies presented in the introduction (i.e. WFA and LCA WF) to better understand their differences and investigate their specific strengths and weaknesses as a support for watershed management.

Since WF is a multidimensional indicator that varies in space and time, a specific production chain at a specific location and time needs be chosen for analyzing the WF. This analysis focuses on the wine production in the water scarce area of "Chianti Classico"(Arno river basin, central Italy, fig.4.2) by WFA methodology and the LAC WF as defined in the ISO 14046 standard .

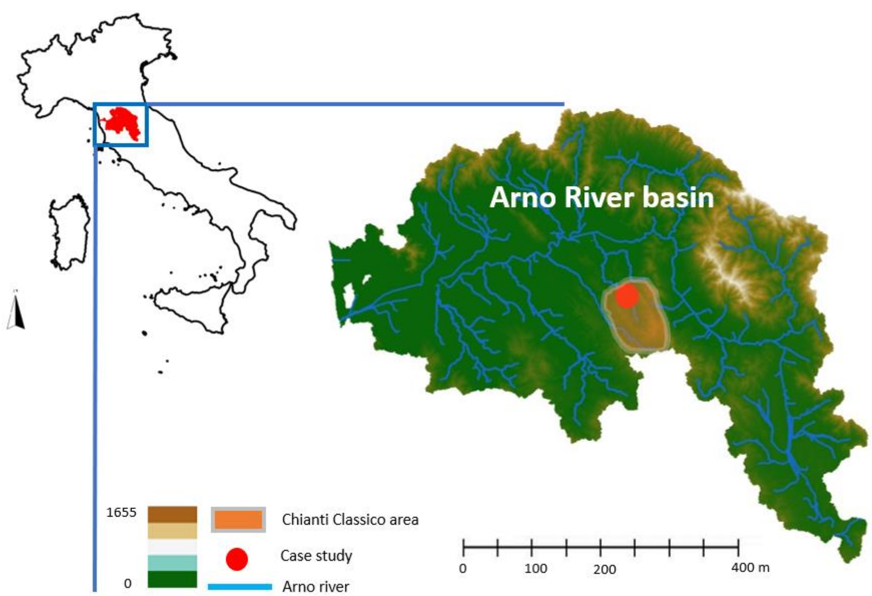

Fig. 4.2 Case study location (boundaries of Chianti Classico area and case study pinpointing)

The case study is approached according to the specific structure of the two methodologies used, as represented in Fig. 4.1. Firstly, the goal and scope definition that is common to both methodologies, is presented. Then, WFA and LCA WF are separately developed, showing their differences and comparing their results.

Goal and scope setting for Water Footprint and Life Cycle Assessment

The scope of the study is the analysis of the WF associated to wine production in a small-medium sized farm in Chianti area (30 ha of cultivated fields). In this phase, the boundaries of the analyzed system and the processes to be included are identified.

The boundaries of the analyzed system are identified as:

- Spatial boundaries: Physical extension of the farm (Fig. 4.3)
- Temporal boundaries: Evaluation of the solar year 2014

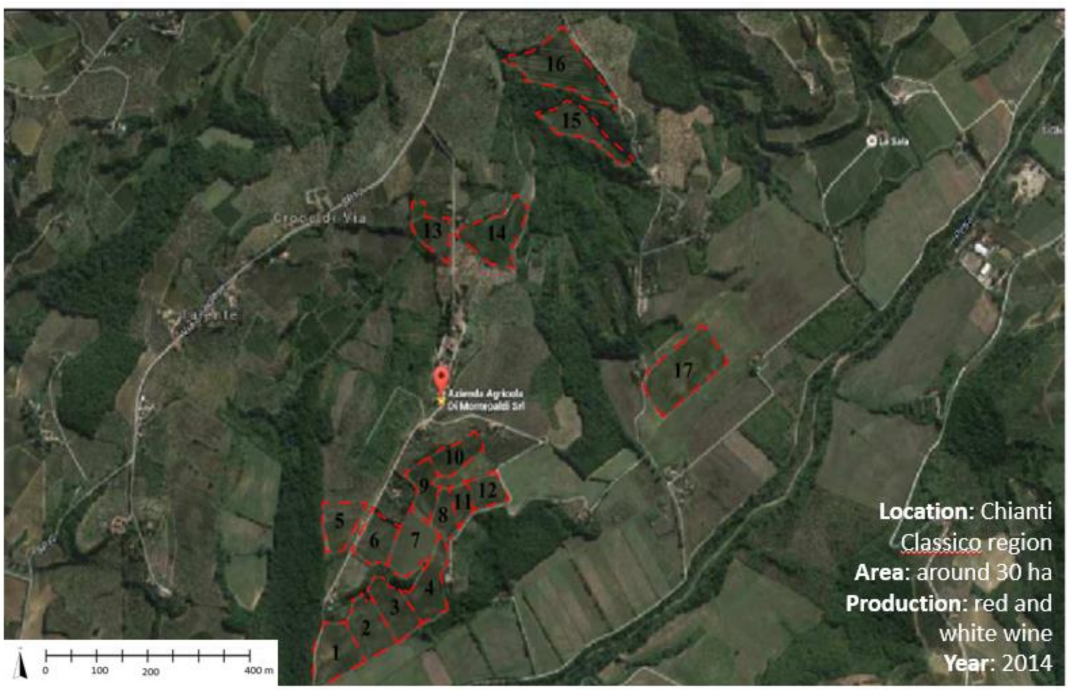

Fig. 4.3 Details of the vineyard plot considered (red lines represent the wine fields)

For both WF and LCA WF, the analysis focuses on the two main stages of the life cycle: agricultural operations and cellar operation up to bottling. The agricultural stage includes all the operations that are related to the field preparation (e.g. ploughing, shredding), the use of fertilizers and other treatments, and the harvesting procedures. The cellar stage considers all the processing techniques of grapes and includes the wine storage (Fig. 4.4). The production and supply of bottles is outsourced and has been considered outside of the scope of the study while the water used for washing has been considered within the cellar consumptions.

The functional unit, i.e. the reference unit to which the inputs and outputs are scaled, is 1 liter of wine. The WF calculation refer to the consumption of water to produce a single liter of wine. The company analyzed produces both red wine and white wine. However, the WF is not differentiated for two types of wine and the calculation was developed considering the total water consumption for the two productions divided by the total number of liters of wine (both white and red) produced (Fig. 4.4).

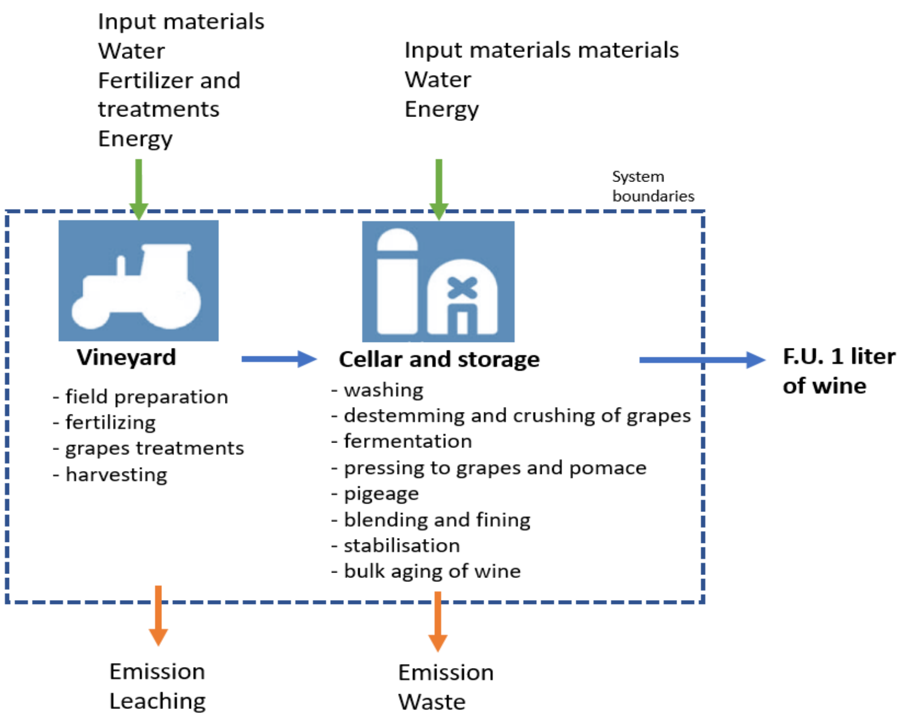

Fig. 4.4 System boundaries of the analyzed system

Water Footprint Assessment (WFA)

Water Footprint accounting

After the goal and scope definition, the WFA is followed by WF accounting, where all the contribution to the total WF are estimated according to the qualitative and quantitative information available. Qualitative information concerns the type of water resources used (e.g. water source identification) and the production chain description, while the quantitative information concerns all fluxes of water and other resources (such as energy or other raw materials, e.g. fertilizer) that will be then converted to water volumes. For each stage a detailed data collection campaign was carried out through questionnaires and on-site surveys. In the following paragraphs, the inventory of different types of water flows (blue, green and gray) required for WF accounting is reported for the two stages of the production chain (cultivation, and cellar stage).

- Agricultural stage

Agricultural stage:

$WF_{agr,\ Blue}=$
$WF[phytosanitary\ treatment]$
$+WF[pesticides]$
$+WF[diesel\ production]$
$WF_{agr,Green}$
$WF_{agr\ ,Gray}$

According to the WFA, the WF of the agricultural stage is made of three components: blue, green and gray WF.

The Blue WF accounts for the direct and indirect consumption of fresh water. The direct consumption of blue water during the agricultural phase has been calculated based on the on-site data regarding the water withdrawals needed for phytosanitary and pesticides treatments (results are referred to the area of cultivation).

WF agr Blue[phyto] = 2.4 m^3/ha

WF agr Blue [pest] = 0.23 m^3/ha

The indirect consumption of water needed for the production of diesel consumed by agricultural machinery is estimated according to literature (Jefferies et al., 2012), assuming a consumption of 0.05 m^3/t (results are referred to the area of cultivation):

WF agr Blue [Prod. Diesel] = $5.181 \cdot 10^{-3}$ m^3/ha

Grapes are not irrigated, therefore the evaluation of the green WF correspond to the estimation of their evapotranspiration (ET). The ET analysis was conducted using the CROPWAT 8.0 model (FAO), a decision support tool for irrigation scheduling developed by FAO.

According to Allen et al. (1998) crop water requirement (ETc) may be calculated as evapotranspiration under standard conditions, by equation 1:

$$ET_c = K_c * ET_0 \quad (1)$$

where ET_0 is the potential evapotranspiration (mm/day) and K_c is a dimensionless coefficient depending on crop type (Allen et al. 1998). In turn, potential ET is estimated according to the so called FAO Penman-Monteith equation (Allen et al. 1998, equation 2), depending on climatic data, which should be collected from the nearest and most representative meteorological station, for each considered geographical location:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (2)$$

where: T is the temperature (°C); U_2 is the wind speed at a height of 2 meters (m/s); γ is the psychometric constant (kPa/°C); G is soil heat flux (MJ/m^2/day); R_n is the net radiation at the crop surface (MJ/m^2/day); Δ is the slope of the vapour pressure curve (kPa/°C); e_a is the actual vapour pressure (kPa); and e_s is the saturation vapour pressure (kPa) (Allen et al. 1998). Data were gathered from the Tuscany regional hydrologic service.

Green crop water requirement is the part of evapotranspired water that can be supplied by the effective rainfall and is equal to the minimum between effective rainfall and the crop water requirement (equation 3, fig. 4.5):

$$CWR_{green} = ET_{green} = \min(ET_c\,, P_{eff}) \qquad (3)$$

P_{eff} is the rainfall that is available in the soil to meet the water needs of the crop. This effective rainfall was estimated according to the method proposed by the United States Department of Agriculture, Soil Conservation Service (USDA SCS, 1970), according to equation 4:

$$P_{eff} = \frac{P_{tot}(125 - 0.2\,P_{tot})}{125}\ for\ P_{tot} < 250\,mm$$

or (4)

$$P_{eff} = 125 + 0.1\,P_{tot}\ \ for\ P_{tot} > 250\,mm$$

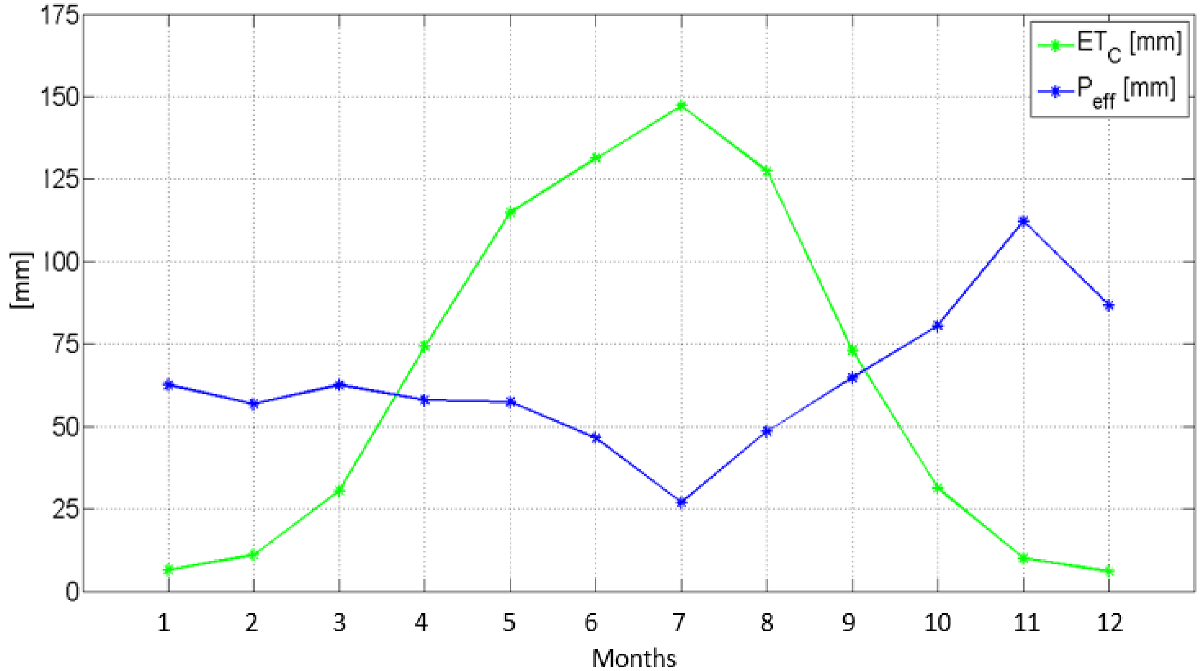

Fig. 4.5 Et_c and P_{eff} simulated with Cropwat

The total crop water use (CWU, in m^3/ha) is calculated by the cumulative value of daily evapotranspiration (ET, mm/day) over the growing period lenght (lgp) :

$$CWU\ green\ = \sum_{d=1}^{lgp} ET\ green \qquad (5)$$

Therefore (results are referred to the area of cultivation):

WF agr Green = CWU_{green} = 3967 m^3/ha

The Grey WF of the agricultural stage is equal to dilution of the most impacting substance used in the farm. It is calculated as:

$$GWF = \frac{\alpha \times Appl}{c_{max} - c_{nat}}$$

where:
α: runoff factor;
$Appl$: quantity of applied substance;
c_{max}: maximum acceptable concentration;
c_{nat}: natural concentration

The runoff factor depends on many factors, among which the properties of the substances applied to the field, the methodology of application, the characteristics of the soil, the climatic conditions and the agricultural practices. To each of these factors (s_i) I attributed a weight w_i to obtain an estimate of the runoff factor that is representative of the case study:

$$\alpha = \alpha_{min} + \frac{\sum_i s_i \times w_i}{\sum_i w_i} \times (\alpha_{max} - \alpha_{min})$$

The maximum acceptable concentration depends on environmental quality standards, while the natural concentration is the concentration that would be in the water body without human intervention.

The Grey WF measures the volume of water necessary to assimilate the load of pollutants, is considered a measure of the deterioration of the water quality. In this case study the major contribution, and therefore the final value of the Grey Water Footprint, proved to be due to the use of copper.

Therefore, the gray WF is equal to the WF associated to copper dilution, resulting in (results are referred to the area of cultivation):

WF agr Gray = GW_{Cu} = 10,981 m^3/ha

- Cellar stage

Cellar stage:

$$WF_{prod,\,Blue}[wine] = WF[cellar\ water\ consumption] + WF[cellar\ electrical\ consumption]$$

The WF of the cellar stage is only blue and it is made of the direct water consumption in the cellar and the indirect water consumption associated to electrical consumption. The direct consumption of water necessary for the vinification phase is assessed through an elaboration of the water volumes data extracted from the farm water bills.

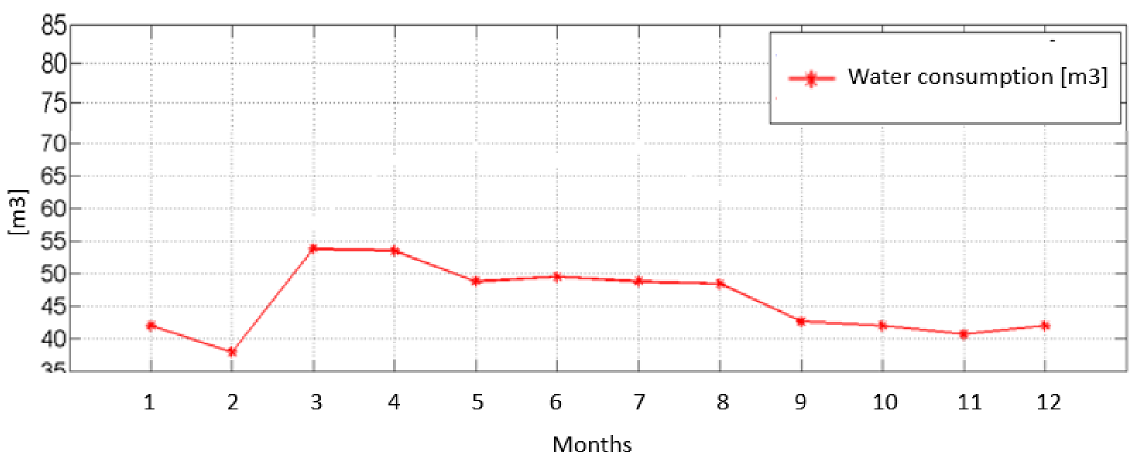

Fig. 4.6 Water consumption at the cellar

The WF associated to water consumption is the cumulated of the monthly consumptions (results are espressed as the cumulative volume consumed in one year):

WF prod Blue [cellar.water] = 549.8 m^3

The indirect consumption of water is related to electricity used in the cellar. Also in this case, the data regarding the electrical consuption is evaluated through the elaboration of the farm electrical bills information.

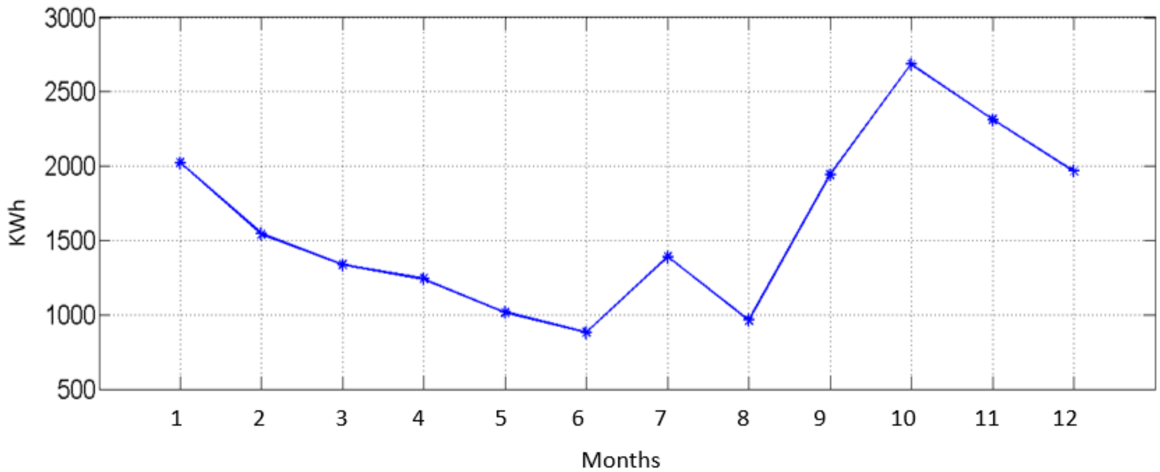

Fig. 4.7 Electrical consumption at the cellar

Based on literature (Pfister et al., 2011), the blue WF due to the production of electricity used by the machinery for cellar operation is assumed equal to 4.47 m^3/MWh.

The WF associated to electrical consumption is: WF prod Blue [electricity]= 86.3 m^3

WFA results

The total WF associated can be estimated converting all the components calculated for the functional unit, i.e. 1 liter of wine. This can be done knowing the field yield (equal to 6.4 ton_{grapes}/ha according to data collecting on-site) and the grape yield (equal to 0.77 $liter_{wine}/kg_{grape}$):

$WF_{l\ wine}$ =WF agr Blue + WF agr Green + WF agr Grey + WF prod Blue

$WF_{l\ wine} = 5.35 \cdot 10^{-4}\ m^3/l + 0.81\ m^3/l + 2.2\ m^3/l + 0.0039\ m^3/l = 3041\ l/l_{wine}$

As shown in Fig. 4.8, the WF is mainly due to the gray component associated to copper dilution, followed by the green contribution. It is important to highlight that the blue WF, i.e. the actual amount of water withdrawn from the system, represents the minimum part of the entire WF.

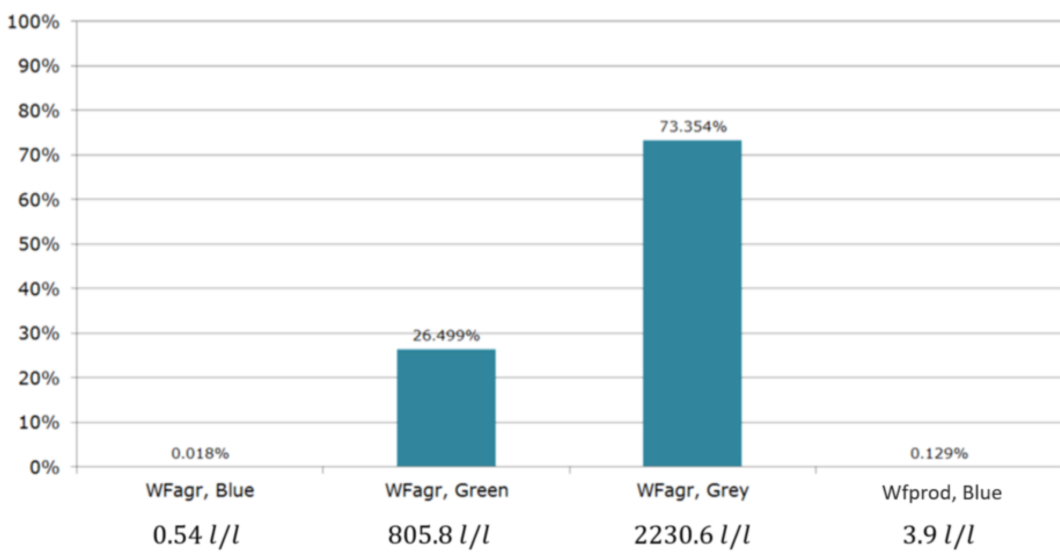

Fig. 4.8 Water Footprint Assessment methodology results

LCA Water Footprint (ISO 14046)

Inventory

After the goal and scope definition, LCA WF requires the inventory of all the material inputs (mainly natural biotic and abiotic resources, including water) and outputs (mainly emissions in gaseous, solid and liquid form, the latter related to water pollution and, hence to grey water) and the entering and exiting energy flows. There are differences between the inputs considered previously for the evaluation with the WFA methodology and those that are considered for the evaluation according to the LCA methodology. In particular, the agricultural stage inventory differs from WFA approach in terms of gray WF, which is calculated in LCA as the contribution of every product with a set of environmental quality indicators (such as ecotoxicity or eutrophication), and green WF which is not evaluated. Also data elaboration is different, because the LCA approach requires a preliminary mapping of all the resources and materials that will be then converted into a WF or other indicators value in the impact assessment phase. Here the inventory of the agricultural and cellar stages is briefly introduced:

- Agricultural stage

The blue WF accounting for the agricultural stage is based on the same data used for WFA. On the other hand, the gray WF differs completely, because it takes into account the entire amount of treatments used in the fields and not only the most impacting.
The use of fertilizers and other treatments was modelled considering the chemical composition of each product and using the related Ecoinvent database inventory processes (Frischknecht et al. 2005). The part of the applied fertilizers that infiltrates in the soil through leaching is calculated according to Franke et al. (2013) (Tab. 4.1).

Green Water was not considered, since - as described by ISO 14046 - it can be assumed negligible, if the production chain does not imply significant changes in the evapotranspiration. Since cultivation of grapes is a traditional activity in the area, it can be assumed that the green WF is not affected by the production chain, maintaining the ET unaltered.

- Cellar stage

The same consumption data of WFA were used.

Tab. 4.1 Inventory for LCA WF. For each impact category, corresponding to each specific stage of the wine production chain, all the processes are described in terms of the quantities of natural resources and materials used.

Impact category	Process	Input (Simapro)	Quantity
Blue Water Agriculture	Produzione di Diesel	Diesel {Europe without Switzerland}; market for; Alloc Def, U	103.6206 kg/ha
	Trattamenti Fitosanitari	Tap water {Europe without Switzerland}; tap water production, conventional treatment; Alloc Def, U	2.4 kg/ha
	Trattamenti Diserbanti		0.2297 kg/ha
Blue Water Cellar	Consumi in Cantina	Tap water {Europe without Switzerland}; tap water production, conventional treatment; Alloc Def, U	549.7766 kg
	Consumi Elettrici	Electricity, low voltage {IT} market for; Alloc Def, U	19.299 MWh
Gray water fertilizing	Concime Minerale	Nitrogen Fertiliser, as N {GLO}; market for; Alloc Def, U	17.2255 kg/ha
		Phosphate Fertiliser, as P_2O_5 {GLO}; market for; Alloc Def, U	8.6127 kg/ha
		Potassium Fertiliser, as K_2O {GLO}; market for; Alloc Def, U	25.8382 kg/ha

Impact category	Process	Input (Simapro)	Quantity
Gray water pesticides	Glifosate	Glyphosate {GLO}; market for; Alloc Def, U	0.9019 kg/ha
	Flazasulfuron	[sulfonyl]urea-compound {GLO}; market for; Alloc Def, U	0.0036 kg/ha
	Glufosinate Ammonio	Organophosphorus-compound unspecified {GLO}; market for; Alloc Def, U	0.2350 kg/ha
Gray water phyto	Dimetomorf	Pesticide, unspecified {GLO}; market for; Alloc Def, U	0.6487 kg/ha
	Zoxamide	Benzoic-compound {GLO}; market for; Alloc Def, U	0.2910 kg/ha
	Cyflufenamid	Pesticide, unspecified {GLO}; market for; Alloc Def, U	0.0697 kg/ha
	Fluopicolide	Pyridine-compound {GLO} market for; Alloc Def,U	0.222 kg/ha
	Fosetil Alluminio	Fosetyl-Al {GLO} market for; Alloc Def,U	3.3335 kg/ha
	Tebuconazolo	Cyclic N-compound {GLO} market for; Alloc Def,U	0.1412 kg/ha
	Fluopiram	Pyridine-compound {GLO} market for; Alloc Def,U	0.1759 kg/ha
	Ametoctradina	Cyclic N-compound {GLO} market for; Alloc Def,U	0.1114 kg/ha
	Fosfonato di Potassio	Pesticide, unspecified {GLO}; market for; Alloc Def, U	0.3619 kg/ha
	Metrafenone	Pesticide, unspecified {GLO}; market for; Alloc Def, U	0.2775 kg/ha

LCA impact assessment

To determine the value of WF according to ISO 14046 all the fluxes of resources and material mapped in the inventory phase must be converted to WF values using specific characterization factors.

The impact assessment was carried out using the SimaPro 7 software according to the ISO 14046 methodology. Only blue and gray water footprint have been considered, as the present cultivation of grapes is not associated to any change in evapotranspiration pattern (i.e. green water) that may affect the water balance. Blue water and grey water were defined as a set of LCA impact categories. The selection of impact categories considered for WF represents a challenging issue since many methods exist and further experience is needed in order to identify the most effective ones. In this study, the blue WF, which results in an assessment of Water Scarcity Footprint (WSF), is evaluated as the impact on the availability of water resources (expressed as cubic meters) according to the methods proposed by Pfister et al. (2009) and Hoekstra et al. (2012). The method is based on regionalized characterization factors that are the Water Stress Indexes (WSI) calculated as weighted averages based on the freshwater withdrawal by country data. Both foreground and background water flows have been regionalized according to the values of WSI for Italy. In the method proposed by Pfister et al. (2009), the WSI is based on a withdrawal to availability (WTA) ratio and modelled using a logistic function to fit the resulting indicator to values between 0.01 and 1 m^3 deprived/m^3 consumed. In the method of Hoekstra et al. (2012), the WSI is based on a consumption to availability ratio (CTA) calculated as the fraction between consumed (i.e. the total water withdrawn minus the return flow to the system) and available water. The latter considers all runoff water, of which 80% is subtracted to account for environmental water needs. The grey water is evaluated by means of a set of indicators from the method Recipe 2008 (Goedkoop et al., 2009) to take into account water degradation: i.e. freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity (Fig.4.9)

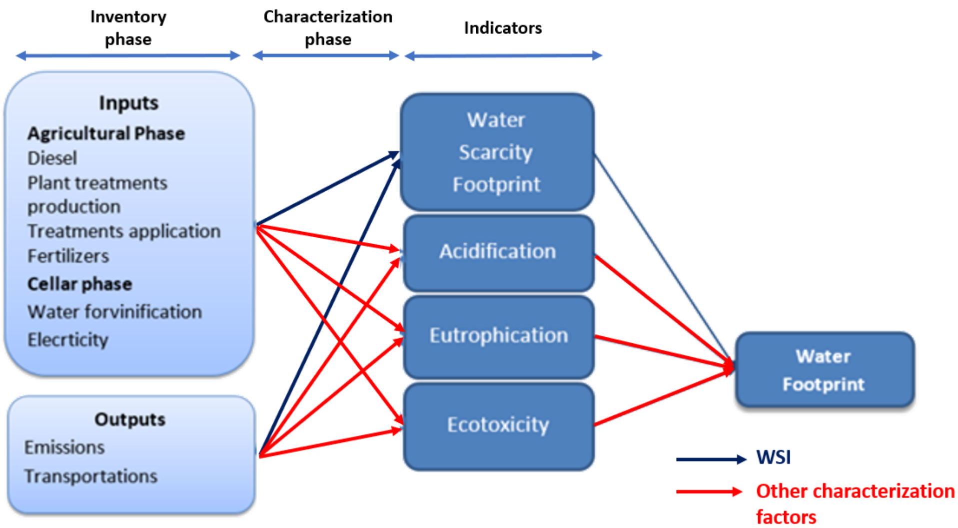

Fig. 4.9 Impact assessment scheme. Inputs and outputs flow identified in the inventory phase are the converted into specific indicators using different characterization factors. All these indicators represent a specific aspect of the overall Water Footprint. The water scarcity indicator, representing the impacts in terms of quantity of water used, has been integrated with indictors describing the water quality.

The Water scarcity footprint results obtained from the two methods are:

$WF_{Pfister} = 2.2\ l/l_{wine}$

$WF_{Hoekstra} = 3.9\ l/l_{wine}$

As shown in Fig. 4.10, the main component is represented by water use at the cellar stage, followed by the water use related to fertilization and other treatments. It has to be noted that LCA methodology also allows for taking into account the impacts associated to production and the emission to water of every chemical compound.

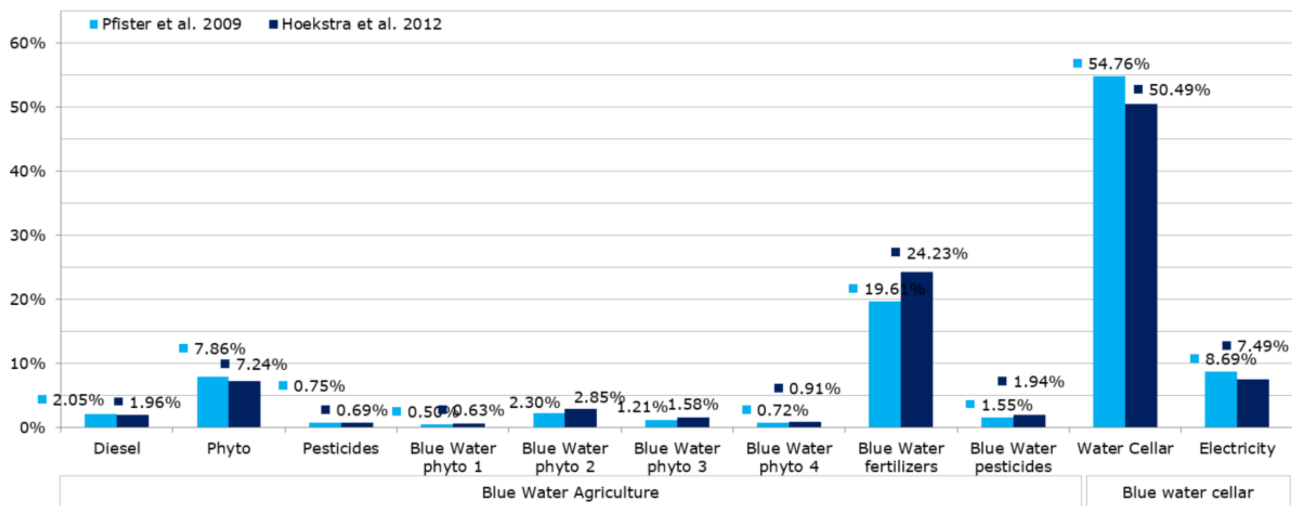

Fig. 4.10 WF distribution in LCA methodology. The blue WF in the agricultural phase is broken up into the contributions related to the different treatment application and the water used for their production (marked with the "Blue water [compound]" label in the graph).

The gray WF is calculated without using volumetric indicators, but evaluating the performances through the use of specific quality indicators from the method Recipe 2008 (Goedkoop et al., 2009). The results show the impacts associated to each step of the production chain, identifying the agricultural stage as the most impacting. In particular diesel production is associated with impacts on terrestrial acidification while fertilizers and treatment application have major impacts on eutrophication and ecotoxicity (Tab. 4.2).

Tab. 4.2 Gray WF impact assessment. For each indicator the most impacting contribution is highlighted.

	Terrestrial acidification [g SO_2 eq]	Freshwater eutrophication [g P eq]	Marine eutrophication [g N eq]	Terrestrial ecotoxicity [g 1,4-DB eq]	Freshwater ecotoxicity [g 1,4-DB eq]	Marine ecotoxicity [g 1,4-DB eq]
Agricultural stage						
Diesel	1.4556	0.0164	0.1249	0.1061	1.0482	927.2
Plant treatments production	0.3653	0.0845	0.0506	0.259	3.0629	3715.8
Treatments application	0.00005	0.000006	0.000003	0	0.0016	0.6
Fertilizers	0.0223	0.3236	0.7757	0.0253	0.0599	49
Cellar						
Cellar water consumption	0.0054	0.0007	0.0081	0.0005	0.0241	23.4
Electrical consumption	0.1201	0.0052	0.1844	0.0116	0.875	359.7
Total Impact	1.9688	0.4304	1.1437	0.4026	5.0717	5075.7

4.3. WF results comparison

Looking at the volumetric results of the different methodologies applied, it appears evident that the results are barely comparable due to the different approaches used. The total WF in the WFA methodology is 3041 liters while the WF in the LCA WF methodology varies between 2.2 liters and 3.9 liters.

The differences between the results can be explained by two main factors:

1. **Green Water contribution:** The green water in the WFA methodology is considered as a consumption while in the WF LCA methodology is considered as contribution only if associated to a change in ET, so it is null in this case study.
2. **Copper contribution:** WFA evaluates the gray WF as the dilution of the most impacting polluting source, while LCA evaluates gray WF with non-volumetric indicators. Therefore, volumetric Gray WF in LCA is only represented by the water used for the application of chemical compounds.

If we consider only the blue water contribution of WFA, the results are comparable to the LCA output. The difference is mainly due to the characterization factors (WSI) that are used in LCA to convert water volumes into WF.

LCA WF results obtained are in line with other studies adopting the ISO 14046 methodology (Quinteiro et al., 2014) and with the values of Blue Water extrapolated by studies adopting different methodologies (Bonamente et al., 2016). However, a numerical comparison with figures from previous studies is quite difficult due to differences in terms of methodological settings and peculiarities of the different case studies. The results provided by this case study are site and time specific, but they represent a starting point that can be generalized implementing other case studies to provide a comprehensive assessment of the entire sector.

4.4. Discussion

WF analysis represents the opportunity of promoting a new water management based on local scale analysis that could raise awareness on the importance of water use at a broader scale. The two approaches used in this case study represent two useful perspectives to look at water management in agriculture. WFA provides a volumetric evaluation of the impacts associated to wine production which is fundamental to water management. Knowing the green, blue and gray components of WF in terms of volumes, provides an important information for analyzing the impact of the sector on local water resources and update the existing knowledge regarding water use. Usually, this knowledge is mainly based on statistical surveys (ISTAT, 2010) which do not consider the real complexity of the problem. In fact, water management planning should be driven by the knowledge of the entire spectrum of impacts on water that is associated with agricultural production and not only focus on declared blue water withdrawals. Only knowing the entire WF associated to agriculture, it will be possible to plan its development and to assess its sustainability. The WFA realized in this case study shows that the impacts on water resources are multiple and affect the water cycle beyond the water withdrawals itself. Our results underline the importance of a detailed analysis regarding the role of green water and its use, as well as the major impacts that pollution might have on water resources.

On the other hand, LCA methodology provides a standard that can be useful at the local scale for the producers who like to improve their knowledge about the impacts of their production, providing synthesis indicators that can set a benchmark for future improvement and allow the producers to get benefits from an internationally recognized standard certification. The main differences with the WFA methodology, i.e. the evaluation of green and gray WF, let the LCA approach seem to be more suitable for identifying solutions for production processes optimization rather than for water management planning.

The integration of the two represent an idea of putting into practice a multiple scale approach. A wise watershed management, supported by WFA, necessarily needs to be supported by tools such as ISO 14046 which allow the development of best practices locally. The debate among LCA and WF methodology should be converted into a win-win situation, where WF in its various meanings support water management at the watershed scale, while raising awareness and promoting a wiser use of water at the farm scale.

5

The water-food security nexus: a method to estimate the effects of inundation on crop availability

5.1. The second face of the water-food nexus

Previous chapters have shown that the understanding of water-food interrelations represents a fundamental step to achieve an appropriate management of the natural resources. It is evident that food security is strictly related to water and both are highly vulnerable to continuously changing climatic patterns (Misra, 2014; Chiarelli et al., 2017; Davis et al., 2017). The previous chapters focus on the water-food nexus from a water scarcity perspective, Chapter 5, in contrast, focuses on the other risk associated to water quantity: floods. Extreme events are causing major water crisis, jeopardizing food security. The climate change report (IPCC, 2014) shows an increasing variability in rainfall patterns demonstrates evidence of flood events increasing in many regions of the planet, according to the Millennium Ecosystem Assessment (MEA, 2005). In addition, land use change can enhance flood risk especially in flash flood prone areas (Rosso and Rulli, 2002). For the above reasons, it has become important to quantify the effects of extreme hydrological events on food production and consequently to food security (Lesk et al., 2016).

Developing countries are mainly affected by these events due to the lack of necessary and essential resources, infrastructures, and adequate disaster management systems (D'Odorico and Rulli, 2013). Furthermore, the effects of natural disasters in developing areas tend to be aggravated by the lack of economic resources, the frequent political instability, wars and conflicts (Zulqarnain, 2013).

According to FAO (2015), between 2003 and 2013, natural hazards and disasters in developing countries have affected more than 1.9 billion people and caused over US-$ 494 billion in estimated damage. The crop production is the most affected subsector (total damages amount to about US-$ 13 billion) and floods are the most impacting natural disasters on agriculture, with a percentage share of damage around 60% (FAO, 2015). Food production will have to increase by 70% in order to feed a population exceeding to nine billion people by 2050 (FAO, 2009). Indeed, it is fundamental to manage agriculture systems, in order to preserve their ecosystem services; such as their capacity to assure food security. According to the definition elaborated by FAO (2001b), food security "*exists when all of the people, at all times, have physical, social and economic access to sufficient, safe and nutritious food, in order to meet their dietary needs and food preferences for an active and healthy life*". In 2009, the Food and Agriculture Organization of the United Nations, FAO, identified the four dimensions of food security as availability, access, utilization, and stability (FAO, 2009).

Flood risk is connected to all the four dimensions of food security. In fact, food availability looks at the "*quantities of food available on a consistent basis*" and the expression "food access" refers to the possibility to have access to enough food for a healthy diet. On the other hand, food use is defined as the "*appropriate use based on knowledge of basic nutrition and care, as well as adequate water and sanitation*", while food stability refers to "*the temporal determinant of food security and affects all three physical elements*" (FAO, 2001b).

Here, I focus on the effects of flood on food availability, in order to develop a methodology to estimate the effects on the short-term food security, i.e. food availability. In this study, the evaluation of food security losses is based upon the integration of remote sensing data and national statistics, which are used to estimate the crops damaged or destroyed by the flood event. On the existing literature-based database related to extreme floods, the floods in Pakistan (2010) and Bangladesh (2007) have been selected as exemplary and complementary case studies, based on the effects of flood events that make a negative impact on food availability. Our analysis related to Pakistan aimed at a general assessment of the effects of flood that affects various types of crop, as well as food stocks. While the Bangladesh case study focuses on rice as the most spread crop found in the country, in order to highlight the importance of considering the peculiarities of each crop in terms of flood resistance. The results are then compared to the average annual food supply and the associated energy content to estimate the direct impacts on food security as lost calories. Additionally, the crops losses are reported in terms of Water Footprint (WF) (Hoekstra et al., 2012), as a complementary indicator to evaluate from a water management perspective the indirect effects of flood at the national nourishment level in terms of water lost.

5.2. Materials and method

Studied areas

The role of agriculture is often studied as a driver of land use change, with potential negative or positive effects on hydrological regimes (Kenyon et al., 2008). On the other hand, hydrological extreme events can cause dramatic consequences on the agricultural land that need to be quantified.

This study aims at assessing the effects of extreme flood events on the food security of hazard prone countries. Many databases of extreme natural events have been created in the last decades. The majority belongs to re-insurance companies, which have made an estimation of damages and victims of several events in order to classify their characteristics and specify a threshold for the definition of a natural disaster. In 2002, CRED (the Centre for Research on the Epidemiology of Disasters) has reviewed the existing literature and databases based on natural disasters. As a result, the review showed that the only freely available database on natural disaster is EM-DATA (2015) developed by CRED itself (Guha et al., 2015).

On the base of EM-DATA database, Bangladesh and Pakistan have been selected as exemplary case studies, because of their vulnerability to floods (Mirza, 2002; Sardar et al., 2008) and the importance of agriculture in their territories (FAO, 2016).

These case studies are characterized by significant differences in their agricultural production and allow us to evaluate the effects of flooding on crops with different resistance to submergence (Butzen, 2016; Jaiphong et al., 2016).

Bangladesh is a developing country in Southern Asia, with a population of 158 million people and a land area of 144 000 km^2, which makes it one of the most densely populated countries (1100 inhabitants/km^2). Most of its territory is flat, with elevation ranging between 0 and 90 meters a.s.l., and 7% of the country is occupied by water bodies – principally by the rivers Brahmaputra, Padma (the Ganges), Meghna and their tributaries. Its tropical climate is characterized by four seasons – pre-monsoon, monsoon, post-monsoon and dry season. Around 80% of the annual precipitation comes during the monsoon season (from June to October), when floods occur regularly, while cyclones occur during the pre and post-monsoon. During the monsoon season, a large portion of the flood water from precipitation and river flow infiltrates into aquifers; it is later used during the dry season.

Around 70% of the population lives in rural areas and 20% is economically active in the agriculture sector, generating around 20% of the country's GDP. 70% of Bangladesh territory is used for agricultural production (FAO, 2016) and the main crop in terms of cultivated area, production and calories intake is rice. According to the Bangladesh Bureau of Statistics (BBS, 2005; BBS, 2009), rice production occurs on more than 80% of agricultural lands and it is grown in three growing seasons (AMAN, BORO, and AUS) that also give the name to the three varieties of crops cultivated.

AMAN grows during the monsoon season when rainfall is plentiful. BORO is restricted to irrigated areas and it grows during the dry season, once the floods have receded. AUS production takes advantage of rainfall during the spring transition toward the monsoon, which enables a short growing season, although the sufficiency of rains varies from year to year (Ruane et al., 2013). BORO is currently the most productive season, followed by AMAN, with AUS considerably lower, mostly due to smaller planted area (FAO, 2008) (Fig. 5.1).

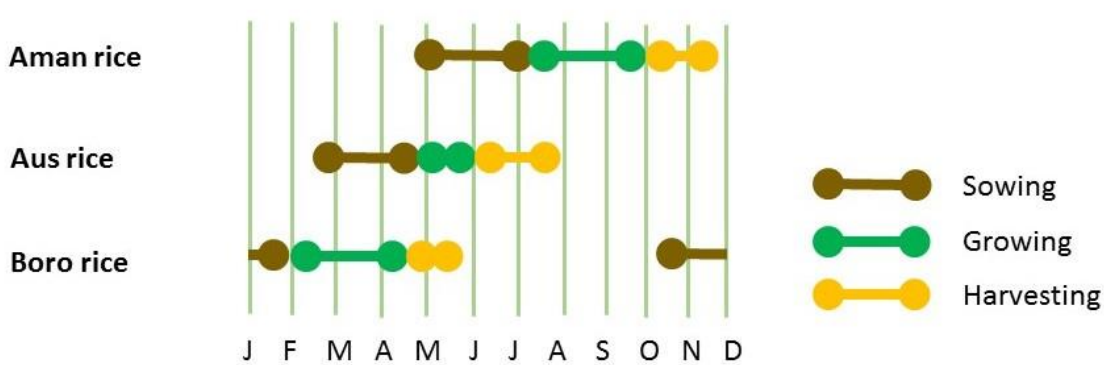

Fig. 5.1 Bangladesh crop calendar (adapted from FAO, 2008)

Irrigation during the monsoon and post-monsoon seasons is secured by the abundant rain, while groundwater is used for the remaining of the year. Therefore, this means that the agricultural sector, and consequently the country's ability to feed itself, relies heavily on rainfall and the capacity of its management. According to FAO FBS-Food Balance Sheets (FAO, 2016) Bangladeshi food supply in 2013 was 2450 kcal/day (2344 and 106 from vegetal and animal products respectively and mainly contributed (76%) by cereals, in particular rice (92%). Domestic production covers the 88% of total food supply, being rice almost exclusively produced in Bangladesh. Food import is 12% of the total consumption, being vegetal oil, pulses and sugar the major imported items, and food export is 0.5%. FAO food security indicators report the 3-year average (2013-2015) depth of the food deficit equal to 120 kcal/cap/day and prevalence of undernourishment and of food inadequacy equal to 16.9% and 26.6%, respectively (FAOSTAT, 2016).

Floods are usual components of Bangladesh's ecology, but extreme events (such as the ones of 1998 or 2007) severely affect the national agricultural production threatening the food security of tens of millions of households (Del Ninno et al., 2013).

The geographical setting of Bangladesh contributes to a historically high number of extreme floods: six extreme flood events (recurrence interval >100 years) have occurred since 1985 (Kale, 2014), mostly caused by overabundant rainfall and inundation of larger rivers, causing considerate damages to all sectors, but principally to the agricultural sector.

In 2007, between early June and September, massive floods caused by the monsoon rains hit the south of Asia. Bangladesh, amongst the neighboring countries, was severely damaged. The floods involved the Padma and Brahmaputra river basins, affecting the nine districts of Dhaka, Munshiganj, Sunamganj, Rajbari, Madaripur, Shariatpur, Manikganj, Netrakona, Jamalpur, Kishoreganj and Tangail.

Pakistan is a developing country of South Asia, with a population exceeding 191 million people it is among the world most populated country. Pakistan covers an area of 796,095 km^2 and it is divided into three major geographic areas: the northern highlands, the Indus River plain (that includes Punjab and Sindh) and the Balochistan Plateau.

The climate varies from tropical to temperate. Arid conditions exist in the coastal south, characterized by a monsoon season with adequate rainfall and a dry season with lesser rainfall, while abundant rainfall is experienced by the province of Punjab. Half of the annual rainfall occurs in July and August.

Pakistan is a rapidly developing country. Fifty percent of its territory is used for agriculture, and this sector accounts for 25.3% of GDP and employs about 43% of the labor force. Punjab province has the highest share of agricultural production, mainly wheat and cotton followed by rice (FAO,

2016) (Fig. 5.2). Pakistan's food production depends greatly on irrigation, which provides more than 90% of the country's wheat and most of the other crops (FAO, 2016).

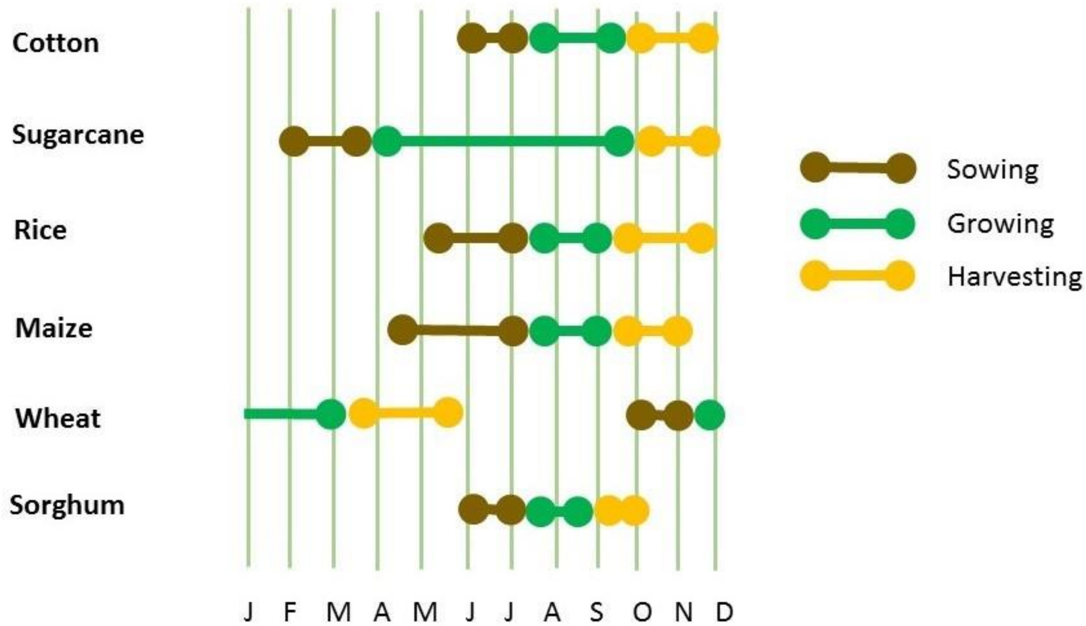

Fig. 5.2 Pakistan crop calendar (adapted FAO, 2012)

According to FAO FBS (FAO, 2016), Pakistan food supply in 2013 was 2440 kcal/cap/day (1910 and 530 from vegetal and animal products respectively and mainly contributed by cereals (48%), in particular wheat (903 kcal/cap/day). Domestic production covers almost the total food supply in terms of wheat and around 75% of rice.

Food import is very low (3%), being palm oil the major imported item and food export is 5% (mainly rice, sugar and wheat). FAO food security indicators report 3-year average (2014-2016) depth of the food deficit equal to 172 kcal/cap/day and prevalence of undernourishment as well as of food inadequacy, which is equal to 22% and 30.5%, respectively (FAOSTAT, 2016).

Statistics show that Pakistan is a country prone to flood: 21 floods occurred between 1950 and 2010 in the Indus Basin, causing cumulative direct economic losses of about $19 billion, killing 8,887 people, and damaging or destroying a total of 109,822 villages (Ali, 2013). The 2010 Pakistan flood analyzed here has been the most damaging event on record, causing around 1600 fatalities. The flood involved the Indus river basin, affecting especially Khyber Pakhtunka, Punjab and Sindh.

Method

The effects of floods on agriculture and the related losses in terms of food security can be calculated integrating remote sensing data with land use assessment and agricultural statistics. Firstly, the evaluation of potentially affected agricultural land is given by the intersection of remotely sensed flood maps with administrative and land use maps of the area of interest. The classification of the flooded area is done following one of the many existing algorithms on the base of raw available data (Ticehurst et al., 2014) or using existing remote sensing product, already classified for flood identification (Sanyal and Lu, 2004).

The potential losses of agricultural land are later converted into effective crop loss taking into consideration the peculiarities of topography, land use and crops characteristics for the selected study area. Additional information, such as specific crop resistance to submergence in terms of time and water depth might be added to refine the crop losses evaluation (Fig. 5.3). The effects of flood on food availability, thus on food security, is finally evaluated by converting crop losses into both lost calories and Water Footprint (WF).

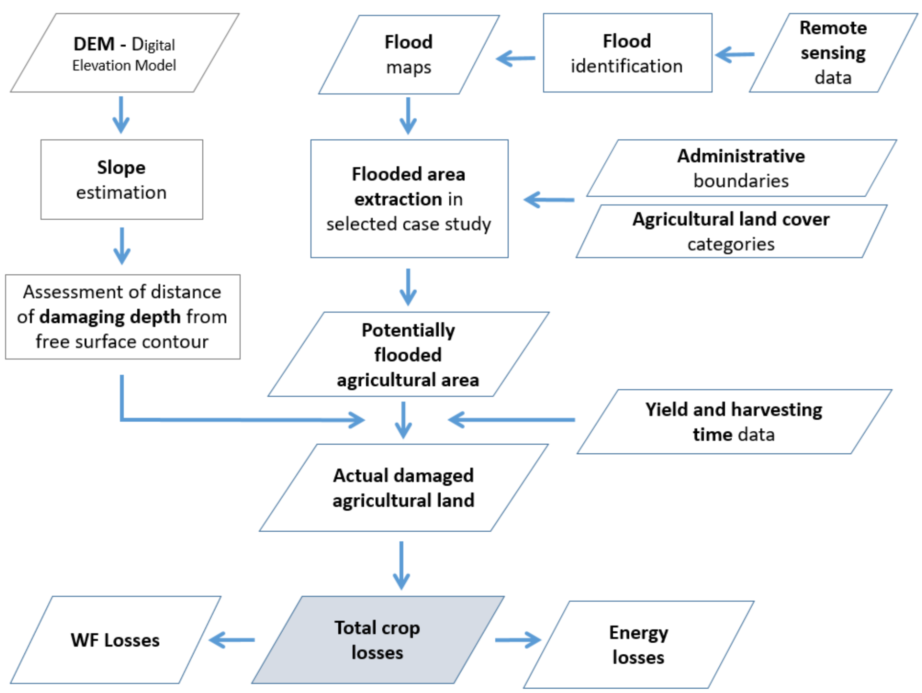

Fig. 5.3 Methodological scheme for estimation of crop losses.

Lost calories are estimated using the specific crop energy content (Schakel et al., 1997) compared to reference Human Energy Requirements (hereafter HER) (FAO, 2001a). HER is defined as "*the amount of food energy needed to balance energy expenditure in order to maintain body size, body* *composition and a level of necessary and desirable physical activity consistent with long-term good health*". The HER varies vastly in terms of age, sex, body weight, physical activity and general lifestyle. According to FAO (FAO, 2001a) a mean Human Energy Requirement is here approximated at a value of *3000* kcal/cap/day. Furthermore, a minimum Human Energy Requirement is approximated at *1800* kcal/cap/day. Taking into account the population, a per capita loss value is determined and compared to food availability levels prior to the floods, in terms of the total energy lost per capita and HER.

On the other hand, the WF associated to flood events can be evaluated from the lost crops, using the crop's WF values available in the existing literature (Mekonnen and Hoekstra, 2011). The results can be then compared to the total WF of an averaged country diet and food supply, derived from FAO data (FAO, 2016).

The WF is an indicator that looks at the direct and indirect use of water of a product. It consists of three components: the green water footprint, the blue water footprint and the grey water footprint. The green WF is the use of rainwater, the blue WF is the use of surface and underground water, while the grey WF refers to the amount of water needed to dilute the water that has been polluted, considering local water quality standards.

In this study, the assessment of WF associated to food losses represents an additional assessment of the vulnerability of a food production system in terms of water availability. In fact, food losses represent not only a lost in calories that directly support human wellbeing but also a loss of water (particularly the blue water embedded into crops, i.e. irrigation) that can influence the future food production.

The use of the two metrics (i.e. energy content and WF) allows identifying the hotspots of land use management both for supporting a complete diet and preserving local water resources. If the percentage of losses with respect to the total country food supply in term of calories is higher than WF, this might indicate the necessity of improving the cultivation management (e.g. changing the crop distribution in flood prone areas) to reduce the risk of losing high calorie crops, fundamental to support local diet especially in food insecure countries not connected to the food market. By contrast, if the percentage of losses in term of WF is higher than in term of calories it could mean that it is necessary to improve crop and water management to reduce, especially in high water scarcity areas, potential blue water losses.

5.3. Application and results

Bangladesh: single crop losses

According to the methodology described in Section 5.2, the potential affected agricultural land can be estimated making use of remote sensed maps of 2007 flood with administrative and land use maps of Bangladesh.

In this study, the remote sensing data provided by the Global Hazards Information Network and UNOSAT are used. In particular, UNOSAT provides the flood map of the 2007 event, based on MODIS Aqua satellite data. This data set contains the detailed flood analysis for Bangladesh, which began on August 2^{nd}, 2007. It includes 30,233 water bodies detected by satellites with a spatial extent of 72,972 km^2 derived from the MODIS-Aqua image acquired on August 2007 and analyzed by UNITAR-UNOSAT (2007) (Fig. 5.4). The land use data are distributed by the Pacific Disaster Center, as institution reference of the Global Hazards Information Network (GHIN, 2008).

Only rice crops are considered, because rice provides almost all of Bangladesh's alimentary needs (BBS, 2009). It is assumed that all of the agricultural areas follow the FAO crops calendar scheme reported in Figure 1, so that only AMAN and AUS rice are considered. In fact, when the floods occurred, the harvesting of the 2007 BORO paddy crop, accounting for some 30% of the annual production, had been virtually completed, while the AUS crop was being harvested and the main AMAN crop was being planted.

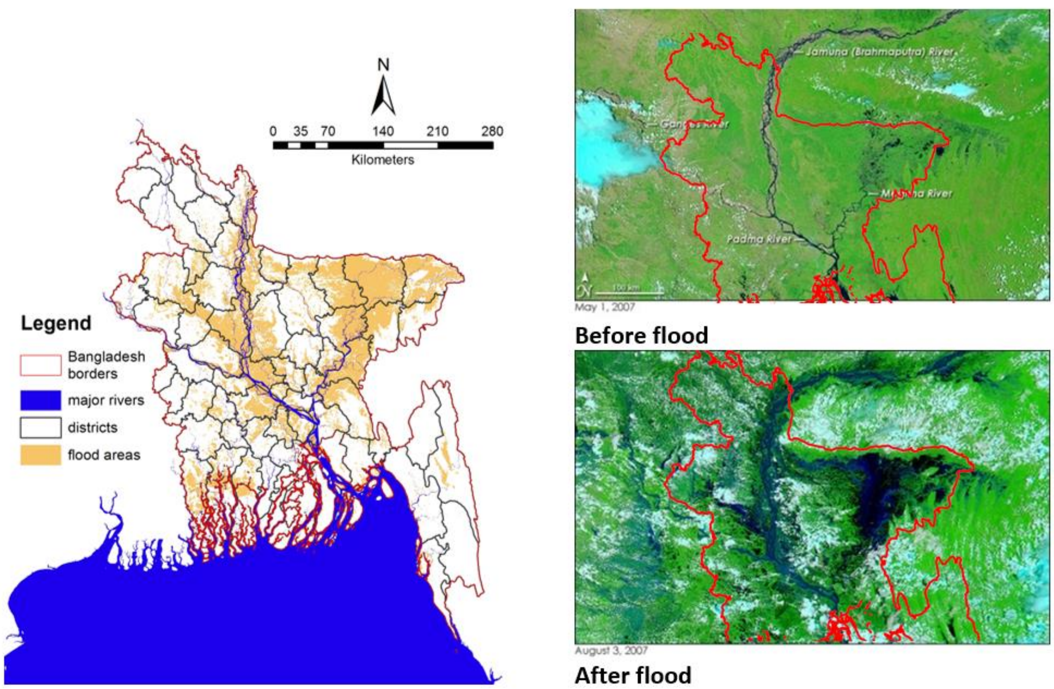

Fig. 5.4 Bangladesh 2007 flooded area (l.h.s.), as identified by MODIS Aqua satellite data (r.h.s.).

Based on yield values derived from the database of the Bangladesh Bureau of Statistics (BBS, 2009; Alam and Islam, 2013) and the remote sensing data of the flooded cultivated area, the hypothetical losses can be calculated, assuming that the flooded agricultural areas lost all the cultivated crops. Similarly, the potential production of rice for 2007 is hereby calculated, considering that all the agricultural area is productive (Tab. 5.1).

Tab. 5.1 Assessment of crop losses (rice varieties) estimated by remote sensing data

Rice variety	Total agricultural area [10^5 ha]	Total agricultural area lost [10^5 ha]	Yield [t/ha] (BBS, 2009)	Potential production in 2007 [10^3 t]	Production losses [10^3 t]
AUS	9.9	0.9	1.66	1,648.7	149.7
BORO	39.3	16.8	3.86	15,142.4	NA[1]
AMAN	60.8	13.2	1.91	11,612.5	2,525
			TOTAL	***28,403.6***	**2,674.7**

[1] not cultivated during 2007 flood

The use of remote sensing data for the estimation of crop production loss can be undermined by the uncertainties related to land use and flood extent estimation. A preliminary check can be carried out by comparing the potential production estimated by satellite data to the actual production (provided by the official sources as FAO and Bangladesh National Bureau of Statistics). In this way, it is possible to quantify the uncertainty in the estimation of the potential rice production. As shown in Tab. 5.2, the estimation of potential rice production made by the use of remote sensing data has a difference less than 5% which is considered acceptable.

Tab. 5.2 Evaluation of remote sensing data performances in crop production estimation and differences between the estimation and the local statitics abailable

	total production [10^3 t]	difference [%]
Remote sensing data	28,404	---
BBS data (BBS, 2009)	28,931	1.8
FAO data (Faostat, 2016)	27,196	-4.4

On the other hand, the total of lost crops derived by the intersection of remotely sensed data of land use and flooded areas (i.e. 2674.7 10^3 t, equals to 10% of the potential rice production for 2007), which results in an unrealistic number compared to the other existing lost crop estimation made after 2007 flood. (i.e. 1200 10^3 t, Habiba et al., 2015). This is due to the assumption that in the flooded area identified by remote sensing all the crops are destroyed. On the contrary, floods affect rice production proportionally to flood hydraulic height and length of the submergence period.

Therefore, a threshold in time and space has been adopted to take into account the resistance of submergence of rice: 1 meter depth (according to deep water areas definition made by Huke and Huke, 1997) and a period of submergence greater than three weeks (according to the International Rice Research Institute, 1976) have been assumed, as the limiting factors to rice growth. Therefore, MODIS satellite images of the 20th August were considered and the flooded area that has a water depth below 1 meter was excluded from the analysis on the base of the topography SRTM data (van Zyl, 2001). In order to calculate the area included within the 0-1-meter depth, the slope of the DEM (SRTM) is calculated and used to estimate the average distance from the points where the water depth is 1 meter to the 0-flood water level (i.e. the flood area perimeter line). The cultivated area not destroyed by the flood is therefore the product of the flood perimeter, times the average distance introduced before (Fig. 5.5). The use of MODIS images from the August 20th (six weeks after the beginning of the flood), guarantees that the time constraint is included.

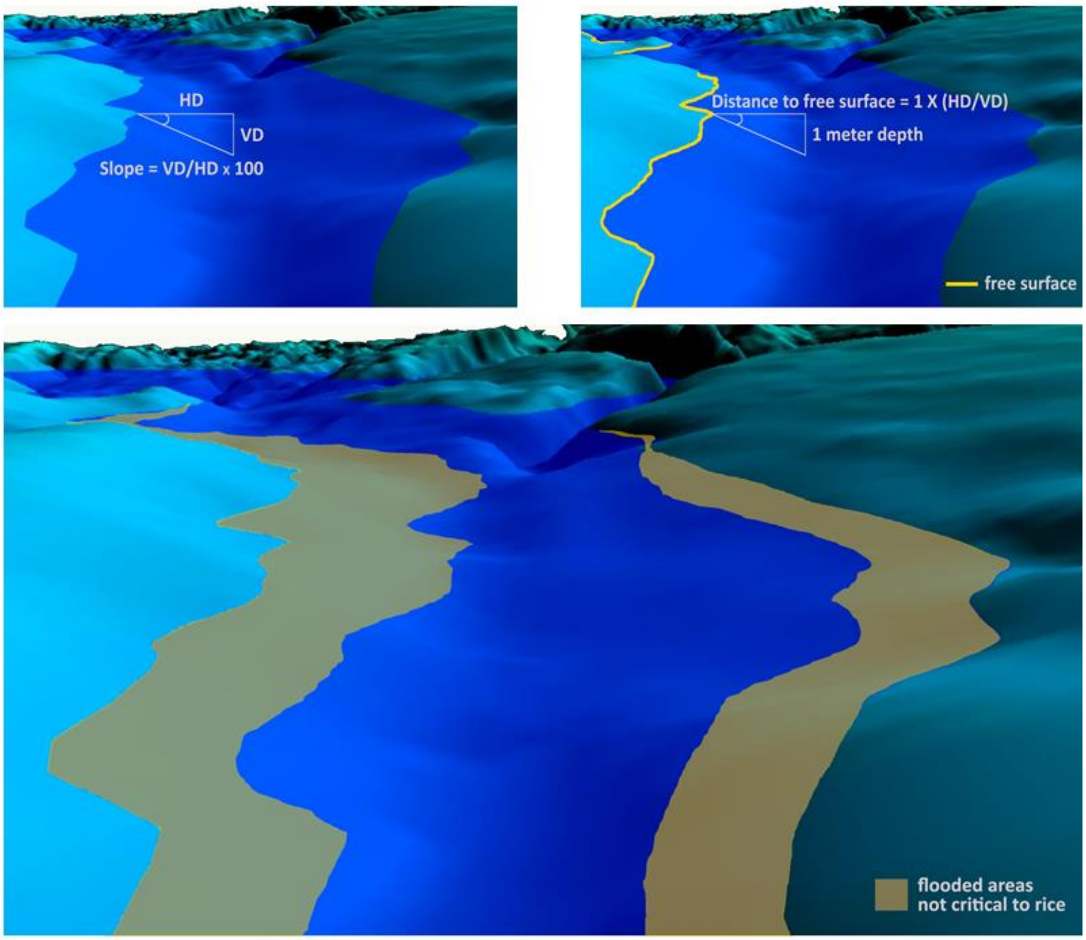

Fig. 5.5 Estimation method of flooded areas not critical to rice for an assumed threshold of 1 meter water depth.

Results show that 5,373 km^2 of the crop flooded area is between 0-1 meters of water depth and thus it is not destroyed. Therefore, this means that the actual rice losses decrease to 1,655.5 10^3 t and the estimated agricultural area lost is 8,728 km^2. This updated estimation is around 30% less than the results obtained without flood depth corrections and it shows accordance with existing estimation, respectively 1,200 10^3 t (Habiba et al., 2015) and 8,900 km^2 (BDER, 2007).

The percentage of lost crops on the potential agricultural production is around 12.5% of the total potential production: this underlines the heavy effect of flood on food production (Tab. 5.3).

Tab. 5.3 Percentages of production lost

Rice variety	Potential production in 2007 [10^3 t]	Actual Production losses [10^3 t]	% lost	Net production [10^3 t]
AUS	1,648.7	84.5	5.1	1,564.2
AMAN	11,612.5	1,571	13.5	10,041. 5
Total	**13,261.2**	**1,655.5**	**12.5**	**11,605.7**

Once the actual production losses are calculated, I estimated the effects on food security by converting the losses to an energy value, i.e. kcal. By knowing the energy content in kcal/kg of rice crops, which in 2007 was an average of 3693 kcal/kg (Wrigley et al., 2015), the quantity of lost rice crops is expressible in calorie supply not provided. The results of Tab. 5.4 show the food energy losses considering that only 90% of the total production of rice is for human use (percentage obtained from Food Balance Sheets, FAO 2016).

Tab. 5.4 Estimation of food energy losses

Rice variety	Production losses for human use [10^3 t]*	2007 flood energy lost [10^{12} kcal]**	per capita energy lost (total population) [kcal/cap/day]***	per capita energy lost (affected area) [kcal/cap/day]****
AUS	76.1	0.281	5	20
AMAN	1,413.9	5.22	98	377
Total	**1490**	**5.50**	**103**	**398**
* evaluated considering that only 90% of the total production is for human use **evaluated multiplying the ton of rice lost by 3963 kcal/kg *** evaluated considering the total population as affected **** considering only the population of the affected areas (i.e. 37,908,436)				

The findings of Tab. 5.4 provide the whole framework of the effects of flood on daily availability of food for Bangladesh population in 2007 (146,592,687; World Bank, 2016): 103 kcal lost represent 5.3% of the potential energy provided by the rice without flood and it is almost equal to the local food deficit. If we consider the effects of flood only on the population of the affected districts (i.e. 37,908,436), the result increases dramatically to 398 kcal lost.

The energy deficit due to the rice production lost, compared to the annual energy provided by the entire food production of Bangladesh in 2006 (FAOSTAT, 2016), using the total kcal/cap/day supply of 2006 (i.e. 2417 kcal/cap/day) is 4.3% if we consider the total population as affected and it raises to 16.5%, if only the population of the affected areas is considered.

To properly understand the meaning of these percentages, it is important to highlight that the lack of food (and thus energy) caused by the flood is contributing to worsen the already critical situation of food supply in Bangladesh. In fact, the energy available from food in Bangladesh is already below the HER, as defined by FAO (3000 kcal/cap/day); comparing the daily per capita calories available in non-flood and post-flood scenario to HER it is possible to have a clearer framework of the food security situation in the country. Bangladesh was already suffering a 19.4% deficit in achieving HER standard and after the flood the percentage of unfulfilled HER has raised up to 22.9% or 32.7%, if we consider only the population of the flooded areas (Tab. 5.5).

Tab. 5.5 Unfulfilled Human Energy Requirements

Energy resources available [kcal]		**difference from HER**	**% of HER unfulfilled**
Total food (food production 2006)	2,417	583	19.4
2007 estimated per capita (total population)	2,314	686	22.9
2007 estimated per capita (for the population of the flooded areas only)	2,019	981	32.7

As presented in Section 5.2, the last step was to translate the obtained results in terms of water footprint and to estimate the number of people affected by the flood.

The amount of water lost with the loss of crops can be calculated using the existing literature data for agricultural products in Bangladesh (Mekonnen and Hoekstra, 2011), containing country's green, blue and grey water footprint data for many types of agricultural products. In particular, for rice crops, these are the reference values: 2118 m^3/ton of green WF, 309 m^3/ton of blue WF, 427 m^3/ton of grey WF. Using the previously obtained data for the quantity of agricultural goods lost, and the provided water footprint of rice for Bangladesh, a volumetric value of the amount of water wasted is obtained (Tab. 5.6).

Tab. 5.6 Water Footprint analysis of rice lost

Rice type	**Green WF [m^3]**	**Blue WF [m^3]**	**Grey WF [m^3]**	**Total WF [m^3]**
AUS	1.79E+08	2.61E+07	3.61E+07	2.41E+08
AMAN	3.33E+09	4.85E+08	6.71E+08	4.48E+09
TOTAL	**3.51E+09**	**5.12E+08**	**7.07E+08**	**4.72E+09**

Considering the WF associated to the average food consumption in Bangladesh, which is equal to 736.9 m^3/year/cap (Hoekstra and Mekonnen, 2012), it is therefore possible to check the estimation made using energy content as a reference for food security (Tab. 5.7).

Tab. 5.7 Affected population estimated by Water Footprint analysis

	Affected population
Total lost water [m^3]	4.72E+09
Consumption per capita [m^3]	7.37E+02
National WF[m^3]	1.08E+11
% of total WF lost (= % of population affected)	4.4%

This estimate represents the attempt of translating the WF analysis of the crop loss due to flood into an estimation of flood magnitude, through the indirect quantification of people affected by flood associated to WF losses. The value of WF lost obtained is very similar to the value obtained considering the energy losses (i.e. 4.3%), this is because the Bangladeshi diet is based on a single crop, i.e. rice. The WF is used as an indicator to evaluate the effects of a flood event to the national nourishment level, representing an alternative and complementary method that can be effective in highlighting the hotspots in a country flood management.

Pakistan: multi crops losses

According to the methodology described in section 5.2, the affected agricultural land is estimated making use of remote sensing derived data that are provided by Suparco and FAO (2010), based on MODIS Aqua satellite and SPOT VGT data. The 2010 flood involved an area with an extension of 58,797 km^2 with duration of about three months, from the end of July until the end of October (Fig. 5.6).

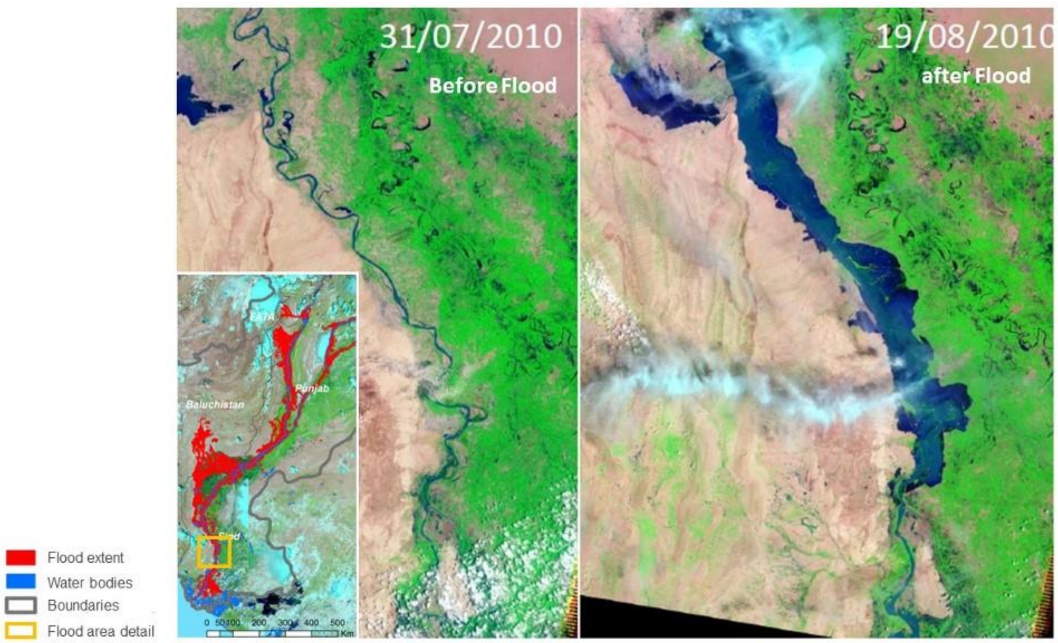

Fig. 5.6 Pakistan 2010 flooded area, as identified by MODIS Aqua satellite data.

All the main Pakistan crops have been considered with detailed data for cotton, sugarcane and rice (SUPARCO and FAO, 2010). It is assumed that all the agricultural areas follow the FAO crop calendar scheme reported in Fig. 5.2. Therefore, in Punjab and Sindh, cotton and other crops such as sugarcane were directly destroyed by the flood, while wheat has been damaged as stock. The characteristics of the crops in terms of yield can be derived from FAOSTAT database (FAO, 2016).

Based on the data provided by SUPARCO and FAO (2010) the cultivated areas that were flooded are estimated. Results show a total of 23,640 km^2 of agricultural areas destroyed, with Punjab and Sind being the districts more affected by the flood (Tab. 5.8).

Tab. 5.8 Districts flooded areas assessment

District	**Cotton [10^3 km^2]**	**Sugarcane [10^3 km^2]**	**Rice [10^3 km^2]**	**Other crops [10^3 km^2]**	**Total [10^3 km^2]**
Balochistan	0.03	0	1.24	0.20	1.47
Khyber PK	0	0.15	0.06	0.41	0.62
Punjab	4.05	1.03	2.36	4.96	12.40
Sindh	1.91	0.76	5.07	1.37	9.15
Total	**5.98**	**1.95**	**8.73**	**6.95**	**23.64**

Using the FAOSTAT, the crops production data for the 10 years before the flood event (FAO, 2016), I calculated an average agricultural yield for the main crops lost (i.e. sugarcane and rice), and estimated the actual crop losses (in terms of weight). By knowing the energy content in kcal/kg of the different crops, I then estimated the associated food energy losses, both in terms of vegetal and animal calories (Davis et al., 2014; Rulli and D'Odorico, 2014) (Tab. 5.9).

Tab. 5.9 Estimation of food losses

	Crop Losses	
District	**Sugarcane**	**Rice**
Total lost area [10^5 ha]	1.95	8.73
yield [ton/ha]	48.81	3.15
Total lost production [10^6 ton]	**9.5**	**2.75**
Energy content [kcal/kg]	300	2800
Energy losses$_{veg}$ [kcal]	**2.85E+12**	**7.7E+12**
Energy losses$_{veg}$ [kcal/cap]	**45.8**	**123.7**

Results show a reduction of production that is about 19% for sugarcane and 40% for rice (comparison made with 2009 production data; FAO, 2016) that is associated to a significant loss of energy available.

Beside the losses of crops directly destroyed in the fields, the food stocks have been also damaged. Based on literature data (Impact Forecasting, 2010) also the damages to wheat stocks have been considered (Tab. 5.10).

Tab. 5.10 Estimation of wheat losses by district

District	Wheat damaged in stocks [10^3 t]
Balochistan	0
Khyber PK	80.8
Punjab	44.9
Sindh	541.7
Total	**667.4**
Energy content [kcal/kg]	3340
Energy losses$_{veg}$ [kcal]	**2.23E+12**
Energy losses$_{veg}$ [kcal/cap]	**35.8**

The sum of crops and stocks destroyed amounts to a total of 205 *kcal/cap/day* lost, due the flood and it is equal to a loss of 8.5% of the Pakistan average food supply (10.7% if we consider only the energy derived from vegetal products).

As shown in section 5.2, Pakistan food supply was already below the HER requirements with a gap of 571 *kcal/cap/day* in 2009 (FAO, 2016). The effects of flood caused an average increase of HER unfulfilled around 26%. The results are even worse if we subdivide the result for the different provinces (Balochistan unfulfilled HER rises to 31%), in particular for Sindh province, in which the values move close to the minimum HER of 1800 *kcal/cap/day* (Tab. 5.11).

Tab. 5.11 Spatial distribution of unfulfilled Human Energy Requirements

District	Energy losses [kcal]	Province population [cap]	Energy losses per capita [kcal/cap/day]	Per capita energy supply 2010 [kcal/cap/day]	Unfulfilled HER
Balochistan	1.09E+12	8,679,650	346.1	2077	31%
Khyber PK	0.54E+12	22,567,090	66.0	2357	21%
Punjab	3.74E+12	93,740,220	109.2	2314	23%
Sindh	7.40E+12	38,190,460	531.1	1892	37%

Based on the existing statistics on WF in Pakistan (Mekonnen and Hoekstra, 2011), I also translated the lost food in terms of water footprint in order to have another measurement of the flood effects on the territory. Results show a total WF of 1.84E+10 m^3 that is equal to 13.5% of the Nation WF (Tab. 5.12).

Tab. 5.12 Water footprint of crop losses

	Green WF [m³]	Blue WF [m³]	Grey WF [m³]	Total WF [m³]
Sugarcane WF	8.74E+08	2.06E+09	2.66E+08	4.25E+09
Rice WF	2.89E+09	9.45E+09	1.19E+09	1.24E+10
Wheat WF	4.89E+08	9.13E+08	2.71E+08	1.73E+09
Total lost water				**1.84E+10**
Annual national WF				**13.66E+10**
% of total WF (= % of population affected)				**13.5**

5.4. Discussion

The method proposed is based on the integration of different sources of information, such as remote sensing data, agricultural statistics and water footprint databases. The application has demonstrated the capability and the limitations of the method in determining the consequences of floods to food supply. It has specifically been shown that the remote sensing data by itself lacks the level of accuracy necessary in a comprehensive food security assessment. On the other hand, the use of remote sensing data, if sustained by other onsite information, can be particularly useful to assess the effects of flood on an agricultural area.

This analysis framework is general and replicable to any location for what concern the use of remote sensing data; some limitation may arise for the data regarding land use and crop characteristics which are strongly site specific and often not easy to collect. A sensitivity analysis has been carried out for the water depth critical to crops in Bangladesh, varying the assumed level by +/- 20%. The results show a difference in the energy content losses estimation of 12% underlying the importance of an accurate choice.

This framework of analysis can help locating the hotspots as high flood risk areas where the crops provide high level of energy or have high water footprint. These are the areas that require proper protection to assure the necessary food production and the proper management to guarantee food security to preserve the available water resources. The two case studies have highlighted the peculiarities of flood effects on countries with different food production systems. In Bangladesh, where the country is basing its food production on one major cultivation the impact in terms of percentage of energy is almost equal to the WF lost. On the other hand, Pakistan show a higher percentage of WF losses compared to energy: this is due to the fact that Pakistan internal food production is more differentiated. Above all, the 2010 flood affected high water demanding crops determining (e.g. sugar cane, rice) determining an higher WF loss (and thus of population potentially affected).

Moreover, the results can be combined with other spatial analysis to provide a broader picture of the flood effects on a territory. An integration of flood extent with population poverty distribution is proposed to identify the hotspots areas where flood strikes the poorest areas (i.e. districts of Netrakon, Kishoreganj and Sumanganj in Bangladesh and Tank, Kashmore, Rajanpur, Ghotki, Thatta in Pakistan), Fig. 5.7.

The strategies for disaster management and planning against flood risk should battle social disparities and focus on these areas that are often more vulnerable and less resilient to flood (Vojinovic and Abbott, 2012). This kind of analysis can provide useful information that help the definition of the priorities of intervention to support the poorest areas in case of flood events.

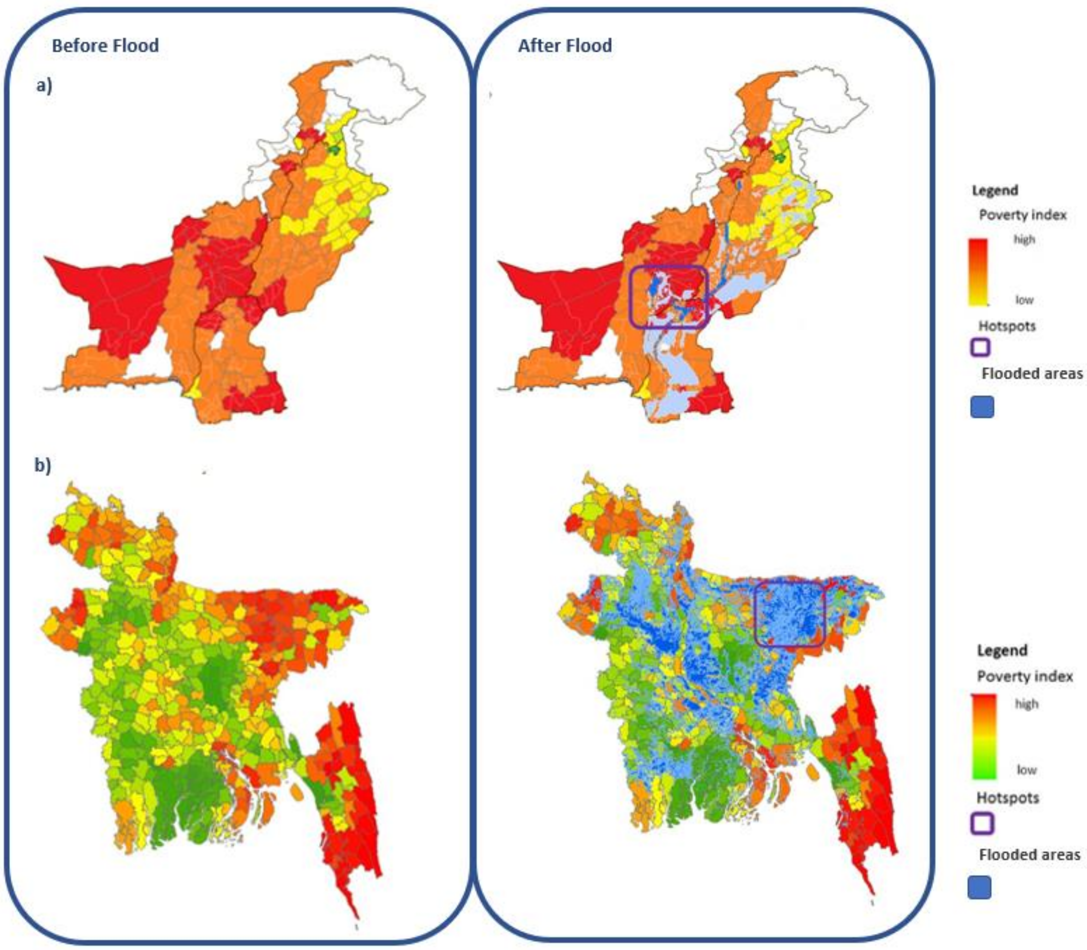

Fig. 5.7 Identification of the poorest area affected by flood (a) Pakistan (adapted from Arshad, 2005), (b) Bangladesh (adapted from Ahmed et al, 2010). The areas more prone to flood (identified in blue) that are also characterized by high level of poverty index (red in the map), are identified as hotspots (marked with the frame).

Both case studies stress the importance of integrating different analysis approaches to carry out an assessment of the meaningful connections between flood and food security and to enhance the resilience of territories. From a nexus perspective, this study allows to clarify how flood management could be crucial also for food production. The analysis of calories and WF losses provides a comprehensive assessment of the inner relationships between food production and water use; in fact, food losses represent not only a lost in calories that directly support human wellbeing but also a loss of water that can indirectly jeopardize food security.

The methodology, taking advantage of the integration of remote sensing data and agricultural statistics, provides a rapid assessment of flood effects on food security on the short term. Moreover, if combined with other spatial information (e.g. poverty distribution, as shown in the case studies), it can provide useful information that can be applied to spatially identify the hotspots and support long term planning.

6

Conclusions and future developments

6.1. Summary and perspectives

The main goal of my research was to investigate the **water-land-ecosystem nexus** at its **multiple scales** to determine an **operative analytical framework** to support **watershed management.** Each chapter deals with a specific aspect of the water-land-ecosystem nexus (Tab. 6.1) .

Tab. 6.1 Summary table of the thesis

Chapter	Objective	Main Findings	Limitations	Outlooks
2- Assessment of water ecosystem services (WES)	Analysis framework development for WES assessment in a catchment	- Spatial explicit estimation of WES - Hotspots identification - Trade-offs analysis	- Focus on surface water only - Cultural and supporting WES not included in the analysis	- Extend the analysis, including all WES classes - Integrate with economical evaluation - Participatory valuation of WES
3 – Ecosystem-based scenario analysis	Ecosystem-based analysis of watershed management strategies	Analysis of the effects of different management strategies on WES	- Only provisioning and regulating services are analyzed - Scenario derived from agricultural policies	- Extend the analysis, including all WES classes - Investigate the effect of different sector policies (e.g. energy) - Merging scenarios with multicriteria analysis
4 – Small scale water-food nexus	Farm scale water footprint analysis (WF)	Comprehensive analysis of water uses for the entire production chain	- Focus on a specific sector - Difficult to generalize results	- Develop other case study for benchmarking - Investigate WES-based characterization factors for WF
5 – The water-food security nexus	Analysis of the implication of floods on food security	Operative and simplified approach to estimate the effects of flood on food security	Uncertainty in the estimations of water depth due to satellite image resolution	- Develop other case study - Use of other satellite data to refine estimation of water depth - Derive indications for territorial planning

A brief recap of each chapter, highlighting the main findings, limitations and possible outcomes is shown below.

Chapter 2: Assessment of water-related ecosystem services to support the Arno river basin management

In this chapter, I quantified the supply and demand of Water-related Ecosystem Services (WES) in the upstream part of the Arno river basin (Central Italy) by integrating hydrological modelling and water accounting analysis. Starting from an existing river management plan based on the Water Framework Directive (WFD), my analysis identified the main water-related issues in the basin as well as the involved WES (i.e. water supply for the different sectors, flow and sediment regulation). I modeled the hydrological behavior of the watershed using the Soil Water Assessment Tool (SWAT) because of its capability to represent a wide range of process that are at the basis of the ecosystem capacity the ecosystem to provide WES.
Based on model outputs, I analyzed the spatial distribution of the WES demand in the basin. Finally, I identified existing hotspots and correlations between WES in the basin to provide a reference for future scenarios development.
The approach proposed in this study could be improved further by reducing the various sources of uncertainty affecting the analysis: beside the inherent uncertainties regarding the hydrological model (Abbaspour et al., 2015), also the estimation of water use within the basin is affected by data quality and assumptions made. The presented case study is focusing only on the assessment of the distribution of WES and their quantification in biophysical terms. Being WES determined by the interactions between human and environment, this analysis has the potential to be integrated with considerations regarding the role of society in determining the distribution of WES and their valuation. Moreover, this analysis focuses on surface water assessment, but the same methodology can be extended to include other aspects, such as groundwater flow to be more comprehensive.

Despite its limitations, the proposed methodology is a useful starting point for seeking a better understanding of the complex relationship between long-term human wellbeing and life-supporting watersheds. In particular, it gives quantitative information on the ecosystem capacity to support human WES demand, highlighting the hotspots and the limits within watershed management moves. The methodology is fully replicable and adaptable to other case studies, being a proper base also for developing WES-based cost-benefit analyses and for supporting decision makers in setting up more comprehensive water management strategies.

Chapter 3: Ecosystem service-based scenario analysis in the Arno river basin

In this chapter, I developed an operative approach based on spatially explicit WES-modelling for assessing the impacts of watershed interventions. Taking advantage of the SWAT model described in Chapter 2, I quantified the responses to different management scenarios in the upstream part of the Arno river basin, namely: (i) afforestation of marginal lands; (ii) implementation of soil conservation measures (e.g. contour ridges); (iii) intensification of the agricultural sector (land use change); and (iv) increased water use in the agricultural areas.

The definition of scenarios and the assessment of alternative intervention options is a fundamental step to improve watershed management by supporting the design of watershed investments. Looking at watershed intervention from the WES perspective can help discovering more integrated solutions. Usually interventions are designed to solve a specific problem, while the results showed that they can have the multiple effects and there are WES trade-offs to be taken into account. Moreover, WES evaluation introduces a fundamental information to improve watershed planning, i.e. the connectivity of territories. In fact, results showed that any intervention produced effects not only at the local scale but influence the overall watershed behavior. This means that a holistic perspective on the watershed is fundamental to derive management plans that are effectively answering all the necessities of the territory.

The main limitation of the analysis is that it focused on regulating and provisioning WES only and it should be integrated with the evaluation of other potential services (e.g. cultural services such recreation or amenities), to provide a more comprehensive assessment. Another limitation is the lack of involvement of actual stakeholders, which lead to develop more assumptions concerning, for example, the selection of intervention sites and the reclassification of land use. A promising outcome of this thesis goes into this direction: A project related to the evaluation of water values by a participatory approach has been recently approved by the regional authority with the support of the Arno river basin authority. This will provide the possibility of investigating the perception of the natural capital value in the territory and will allow the exchange between different perspectives. The scenario analysis presented in this chapter, will provide the preliminary base of knowledge to a spatially explicit prioritization process for water management.

Chapter 4: The small-scale water-food nexus: Water Footprint analysis as a tool for enhancing water use and support water management

In chapter 4, I used and compared different Water Footprint (WF) approaches to evaluate impacts of human activities in terms of water use and impacts on the hydrosphere. In particular, I compared the two existing WF approaches, Water footprint assessment (Hoekstra et al., 2011) and LCA WF (ISO 14046) in a case study for wine production. The analysis highlighted their differences and potential synergies to support a better understanding of water use. The results of the analysis represent a benchmark for future investigations on the impacts of wine production.

This part of the research provides an innovative starting point by considering a single case study, which can easily be replicated and extended to water strategic sectors to generalize the results obtained and to provide even more useful information for environmental resource planning and management.

The study shows that the different WF methodologies represents an opportunity to provide an operative answer to the need of precisely quantifying water use. Regarding the choice among different WF methodologies, a future comparative research is desirable to better understand the influence of contextual differences on appropriate WF estimation and to provide generalizable conclusions at the watershed scale and guidelines to improve the use of water resources at local to regional scales. Based on WES assessment it would be also interesting to explore the possibility of deriving WES-based characterization factors (Gao et al., 2014).

Chapter 5: The water-food security nexus: a method to estimate the effects of inundation on crops availability.

Here, I developed a methodology for evaluating the effects of floods on food supply by integrating remote sensing data, agricultural statistics, and water footprint databases. I applied this methodology to two different case studies, based on the existing literature related to extreme floods: the flood events in Bangladesh (2007) and in Pakistan (2010).

Results showed that the use of remote sensing data combined with other sources of onsite information is particularly useful to assess the effects of flood events on food availability. The damages caused by floods on agricultural areas are estimated in terms of crop losses and then converted into lost calories and water footprint as complementary indicators.

This analysis focuses on direct flood damages to crops or food stocks. Food security could be strongly reduced by flood damages on pasture land, livestock, fisheries affecting directly or indirectly the animal calories and protein food intake (Davis et al, 2014). Additional side effects of flood events, such as the deposition of sediments on fields, the erosion of agricultural soil, the loss of soil nutrients as well as microbial and fungal activities are not explicitly considered here but could be an obstacle for future cropping possibilities and should be taken in account, too (Pimentel et al., 1995; Zhang et al., 2017). Other factors influencing future production may be the spread of insects that could be dangerous to cultivation due to the presence of stagnant water (Rosenzweig et al., 2001). The methodology is fully repeatable, but, whereas for remotely sensed data the sources of data are valid worldwide, the data regarding land use and crops characteristics are strongly site specific and might be difficult to collect.

The three case studies presented represent different components of the general assessment rationale presented in the first chapter. They can be considered three tiles that are pivotal to compose the overall picture of watershed management (Fig. 6.1).

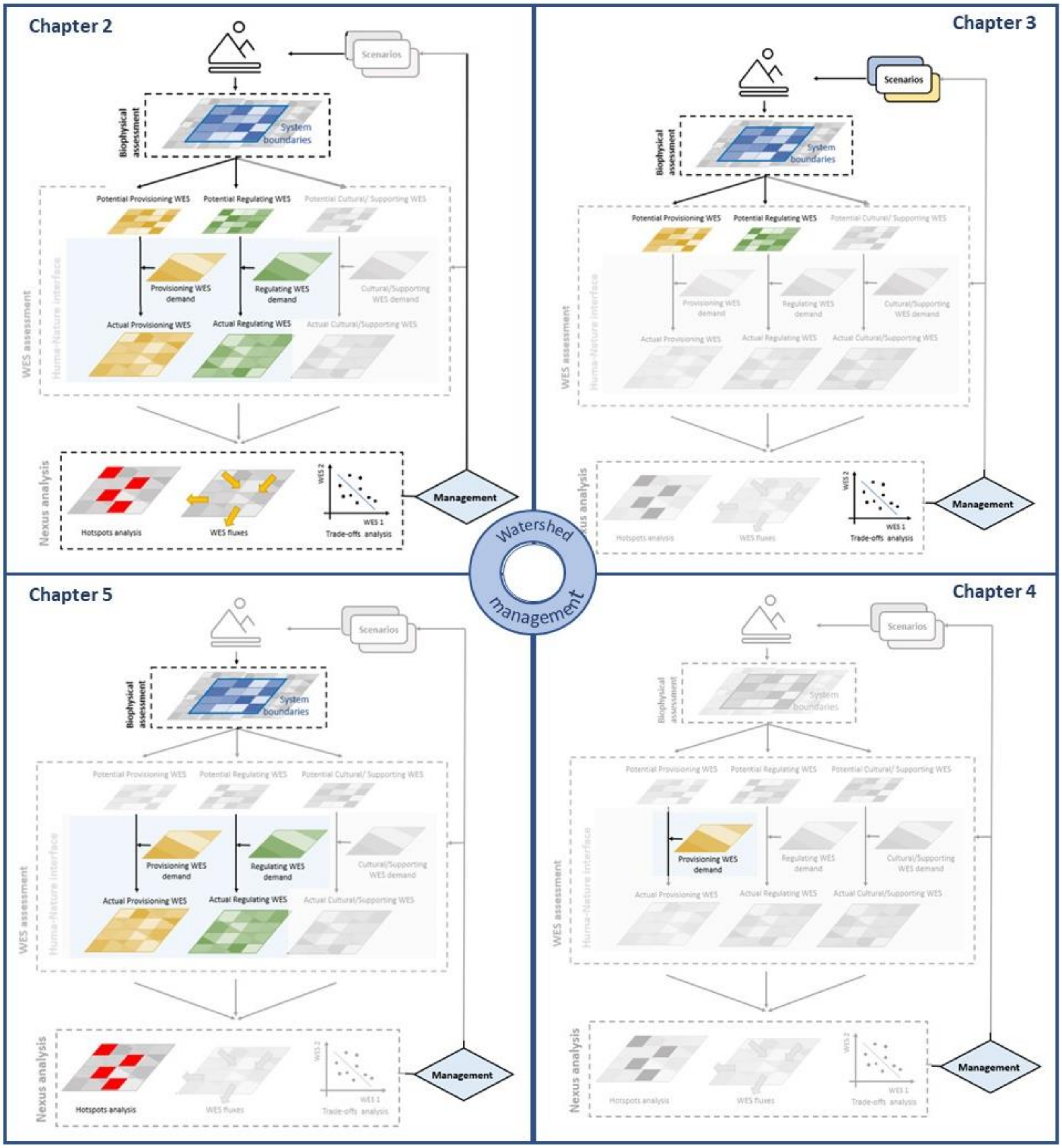

Fig. 6.1 General investigation framework with identifications of the focus of each case study. In chapter 2 and 3, the WES assessment and the ecosystem-based analysis of management scenario, provide useful information to promote a better allocation of WF and to reduce water related risks (i.e. scarcity and regulation). Chapter 4 provides a detailed focus on the demand side, aiming at the promotion of best practices regarding water use that can affect the watershed scale. In fact, WF analysis is a tool to enhance the productivity of WES, thus reducing the vulnerability to scarcity. In chapter 5, I provide an analysis of flood effects on WES (i.e. food production) that can support a better management of crops and their associated WF to enhance the resilience of agricultural system to flood risk.

In each chapter I identified the multiple benefits/risks associated with water and land in the ecosystems. From a water-land-ecosystem perspective, sustainable watershed management should start from the identification of the ecosystem potentialities and limits to derive strategies that can maximize the overall WES production (Fig. 6.2). Each case study provides the tools to support sustainable watershed management at its multiple scale.

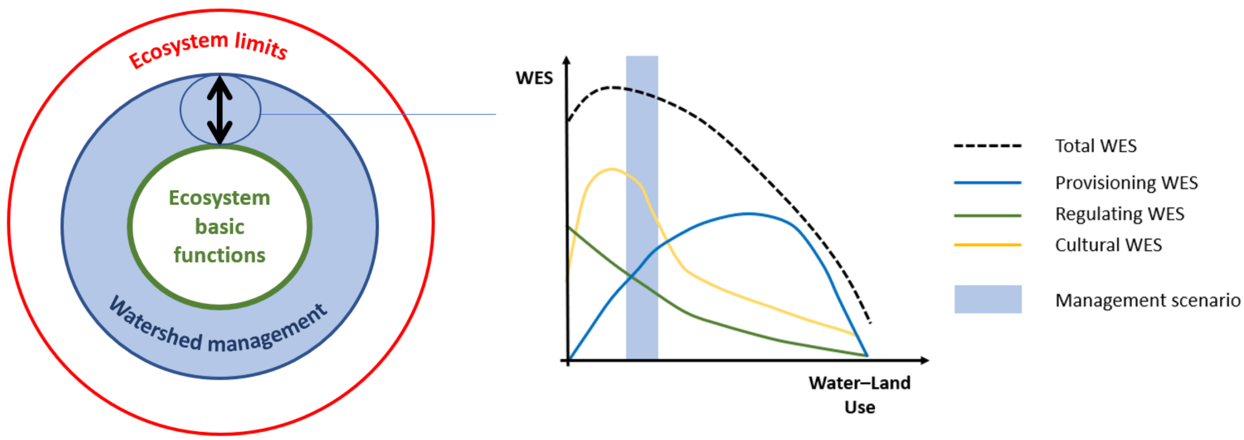

Fig. 6.2 Watershed management from a water-land-ecosystem perspective. Sustainable watershed management options are confined between the necessity of maintaining ecosystem basic functions and the maximum capacity of the ecosystem to provide ecosystem services.

6.2. Conclusions and outlook

At the present time, the relationship between humans and nature is increasingly deteriorating. It appears that the human continuous development is incompatible with the surrounding environment. We tend to search technical solutions that overcome this problem, believing that the progress will provide answers to solve our controversial relationships with nature, but it becomes more and more evident that humans might more reasonably aim at a fair coexistence with nature rather than its dominance. Thus, it is fundamental to promote a “contamination” of the technical approach, enlarging the natural resources management paradigm with the instances raised by ecology, sociology and ethics.
Since water is the fundamental element of our life, rethinking its management can be a chance to start rebuilding the connections that tie human with nature. Starting from this idea, my thesis focused on the role of water in the ecosystems to frame its management from a wider perspective. Since water is the vital connecting matrix in ecosystems, its study implies to deal with the multiplicity of drivers influencing its management.
Taking advantage of existing concepts, such as ecohydrology, ecosystem services and water footprint, I developed a transdisciplinary approach, presenting an analysis framework that is made of different tools to deal with water-land-ecosystem nexus and to innovatively frame the management challenges of a watershed.

The concept of water-related ecosystem services helped me to interpret the water-land-ecosystem nexus in terms of human-nature connections. The multiple benefits we can derive from water (e.g. water supply, food and energy production) represent exactly the idea of nexus. This implies that dealing with the nexus means to deal with the wide range of ecosystem services natural resources can produce. On the other hand, WF gave me the possibility to highlight the role of water in supporting our socio-economic systems and to translate this information into a simplified indicator.

The thesis has provided insights into the role of water and its value at different scales. The water-land-ecosystem nexus is investigated in chapter 2 adopting the classical watershed reference scale, while in chapter 3 I showed how policies that are developed based on other reference scales (e.g. agricultural policies) influence the watershed scale. From a nexus perspective, a watershed should be considered as a control volume to analyze the effects of policies that have a different spatial reference. In chapter 4 I exemplified the importance of analyzing water-land connections at the local scale to cope with water scarcity risk, while in chapter 5 I explored the water-land-ecosystem nexus associated with flood risk at the country level.

The entire thesis dealt with the idea of safeguarding of natural resources, interpreted as a fair coupling of WES capacity and demand. All case studies exemplified the risk associated to a mismatch between WES demand and the capacity of the environment to satisfy it. The role of ecosystems in providing services to humans is fundamental, but it has to be recognized as limited.

WES have specific thresholds, and their co-existence is driven by rules (synergies, trade-offs) that we need to understand. From a water-land-ecosystem nexus perspective, the final target of watershed management should be the equilibrium between supply and demand of WES. This utilitarian expression that is often associated to ecosystem services (Jax et al., 2013), does not imply that human-nature relationship should be approached as a market problem. On the contrary, dealing with WES means to deal with the multiple dimensions of water values. Ethical and economical perspectives should walk together to provide adequate solutions for water management. Several examples going into this direction can be found in the recent literature: e.g. ecosystem services multi-criteria and cost-benefit analysis (Saarikoski et al., 2016), payment for WES to support watershed development (Bellver-Domingo et al. 2016), as well as participatory approached to determine WES values (De Vreese et al., 2016).

A water-land-ecosystem nexus approach and perspective unfolds a wide range of opportunities to change the water management paradigm. An active dialogue between scientific community, environmental management institutions and all the other stakeholders is needed to promote an efficient translation of principles into practice.

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